Department of Energy
Washington, DC 20585

September 27, 1993

Mr. Steven A. Barsony
U.S. Department of Transportation
Federal Transit Administration
400 Seventh Street, SW
Washington, DC 20590

Dear Mr. Barsony,

In response to your request of September 8th, enclosed is the information on the joint DOE/FTA Fuel Cell/Battery Bus Program. More specifically, there is a 12-page summary of the program since its inception, a 3-page detailed summary of funds expended, and a set of briefing charts that may be useful for your presentation.

Sincerely,

John J. Brogan
Director, Office of Propulsion Systems
Transportation Technologies
Energy Efficiency and Renewable Energy

THE PHOSPHORIC ACID FUEL CELL/BATTERY POWERED BUS SYSTEM

BACKGROUND

A review of the status of fuel cell technologies led to the initial selection of the phosphoric acid fuel cell as being sufficiently compact, efficient and cost-effective for an initial application in transportation. In addition, it is the only fuel cell system that is sufficiently developed to permit demonstration and evaluation in a vehicle. The transit bus was selected for the first application of fuel cells because the bus size permits accommodation of the phosphoric acid fuel cell designs. Another factor in selecting the transit bus is the long service life of these vehicles which allows the amortization of the initially higher capital costs over a reasonable time period. Since transit buses operate primarily in urban areas, the quiet operation and low pollution of the fuel cell powered buses will be of particular significance.

The Fuel Cell/Battery Powered Bus System Program was initiated in FY 1988. The objectives of this program, co-sponsored by DOE, DOT/FTA and California South Coast Air Quality Management District (SCAQMD), is to show the feasibility of a methanol-fueled phosphoric-acid fuel cell/battery propulsion system for a small urban bus application and to advance the fuel cell/battery and control technologies in an integrated fashion with available powertrain technology so as to provide an alternative for diesel-powered buses.

The urban transit bus was selected as the entry point for application of fuel cells for transportation because operation in urban areas will accentuate environmental benefits; the transit route structure is relatively fixed and permits evaluation under controlled conditions; the transit industry has an infrastructure in place to support operation and evaluation of the fuel cell/battery bus; the long service life of transit buses allows the amortization of higher acquisition cost over a reasonable time period; and the bus size permits accommodation of the first generation fuel cell designs.

The overall program is divided into four phases as shown in Chart 1.

Phase I - Proof-of-Feasibility

Phase I was a system design/integration effort directed at demonstrating proof-of-feasibility for the fuel cell/battery propulsion system. Key activities included:

(a) Conceptual design of the bus system,

(b) Trade-off analyses and performance specifications, and

(c) The design, fabrication and laboratory evaluation of a half-size fuel cell/battery brassboard propulsion system.

Both air-cooled and liquid-cooled phosphoric-acid fuel cell systems were evaluated in two separate cost-shared industrial contracts, one with a team led by Energy Research Corporation (ERC), and the other with a team led by Booz-Allen & Hamilton (BAH).

The two teams independently began with a conceptual design of a bus system and component requirements. Trade-off analyses were conducted to determine the optimum design and component specifications generated. During this process, economic analyses were performed to insure that the design was economically feasible and had the least cost possible. A brassboard propulsion system was built from the component specifications and each team demonstrated the performance of components and the system.

The results were evaluated to determine which systems would be the best for use in a transit bus. Schematics of the air-cooled and liquid-cooled systems are shown in Chart 2.

A comparison of each team's bus design and performance characteristics compared to a diesel powered bus is shown in Chart 3. Note that even though the fuel cell bus is heavier, it performs better than the diesel bus and its energy consumption is less than the diesel bus.

Brassboard Test Results

Both BAH and ERC met or exceeded design specifications. No fundamental design problems were uncovered and both systems successfully demonstrated the ability to handle rapid load changes encountered in typical bus operation. Ultra-low emissions and low noise levels were also confirmed.

Phase I Conclusions

Based on the results of the Phase I effort it can be concluded that a fuel cell/battery powered urban bus is technically feasible and practical. The life cycle costs of the fuel cell/battery bus can be economically competitive with the diesel and offers additional undetermined economic benefits through improved acceleration, lower noise and very low emissions. The liquid-cooled system potentially has lower fuel and life cycle costs than the air-cooled system.

Since both systems demonstrated the feasibility of meeting bus requirements, the Department of Energy proceeded with the Phase II development effort on a competitive procurement from bidders of either air or liquid-cooled fuel cells.

Phase II - Proof-of-Concept

The Phase II contract requires the design, fabrication and integration of three 25-30 ft test-bed buses (TBBs), using standard off-the-shelf components to the extent feasible. Emphasis is on a rugged design that meets bus industry standards with acceptable performance. The liquid-cooled PAFC technology was selected for further development based on superior system efficiency, packaging possibilities, and the proposing team's technical merits.

Although no new technology development is part of this phase, the major components - the fuel cell and the surge battery - have not been used in the hybrid configuration for transportation applications. The major challenge is in the integration of these components with the proven bus components for safe, economical operation. System integration is therefore a key element of the project.

The contract team includes six companies headed by H Power Corp., which is responsible for project management, system integration, and testing. Bus Manufacturing U.S.A., Inc. is fabricating and assembling three test-bed buses. Fuji Electric Co. is providing the fuel cell subsystem. Soleq Inc. is supplying the propulsion system and electronics. Booz•Allen & Hamilton, Inc. is performing systems analyses and preparing the test plans, and the operating and maintenance manuals. Transportation Manufacturing Corp. is developing a design concept for a standard 40 ft transit bus and providing the benefit of bus industry experience to the team. The team is committed to the commercialization of fuel cell-powered transit buses, as evidenced by a 23% cost-share and top management involvement from each participant in the project.

The schedule for the Phase II effort is shown in Chart 4.

Current Status

The three test-bed buses are in various stages of fabrication and assembly. TBB-1, which is scheduled for delivery in May 1994, is nearing completion. An integration schedule is shown in Chart 5.

The bus configuration is summarized in Chart 6. The bus is powered by a nominal 50 kW fuel cell and a 216-Volt 200 amp-hour nickel/cadmium battery.

The fuel cell subsystem is shown in Chart 7.

A photograph of the assembled test-bed-bus is shown in Chart 8.

Performance

Projected performance is compared with FTA guidelines in Chart 9.

Preliminary Conclusions for Phase II

The fuel cell/battery powerplant offers many significant advantages over conventional transit bus power plants. Ultra-low emissions, higher fuel economy, no noise, smoother acceleration, regenerative braking, reduced brake wear, and low maintenance.

Many challenges remain after this phase is completed. The needed improvements have been identified. Chart 10 summarizes the areas in which further research and development is needed to make fuel cell buses viable.

Phase III - 30 Ft Test-Bed-Bus Evaluation

Track testing and field evaluation of the test-bed buses will be accomplished in Phase III.

Phase IIIa - Product Improvement

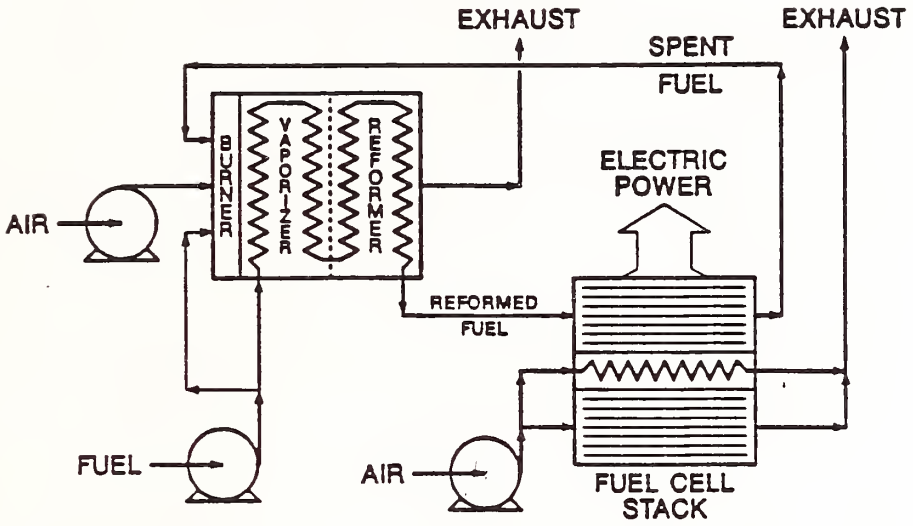
The findings of Phase II and the testing and field evaluation of Phase III will be utilized to improve the bus design. Several areas of improvement have been identified in Chart 10.

CHART 1

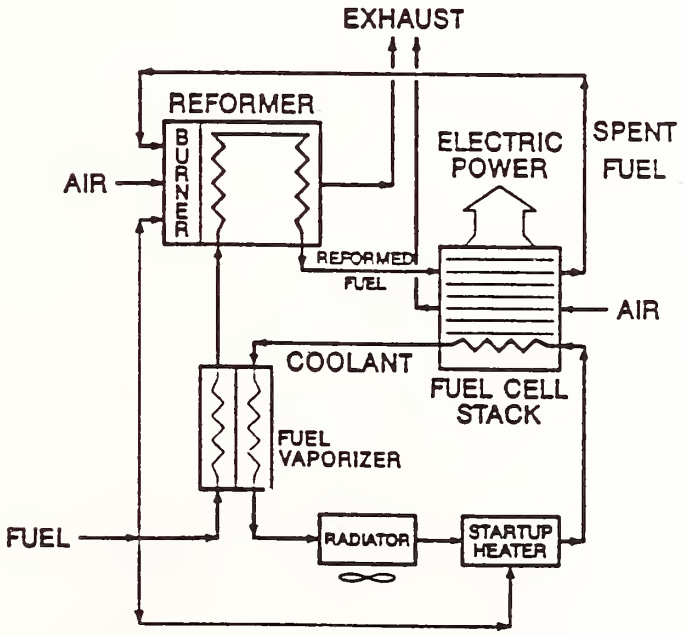
THE PHOSPHORIC ACID FUEL CELL/BATTERY BUS PROGRAM

Phase		Start	End
I	Proof-of Feasibility	4/88	2/90
II	Proof-of-Concept	4/91	10/94
III	30 Ft TBB Evaluation	7/94	12/95
IIIa	Product Improvement	7/94	6/96

CHART 2



Air-cooled phosphoric acid fuel cell subsystem.

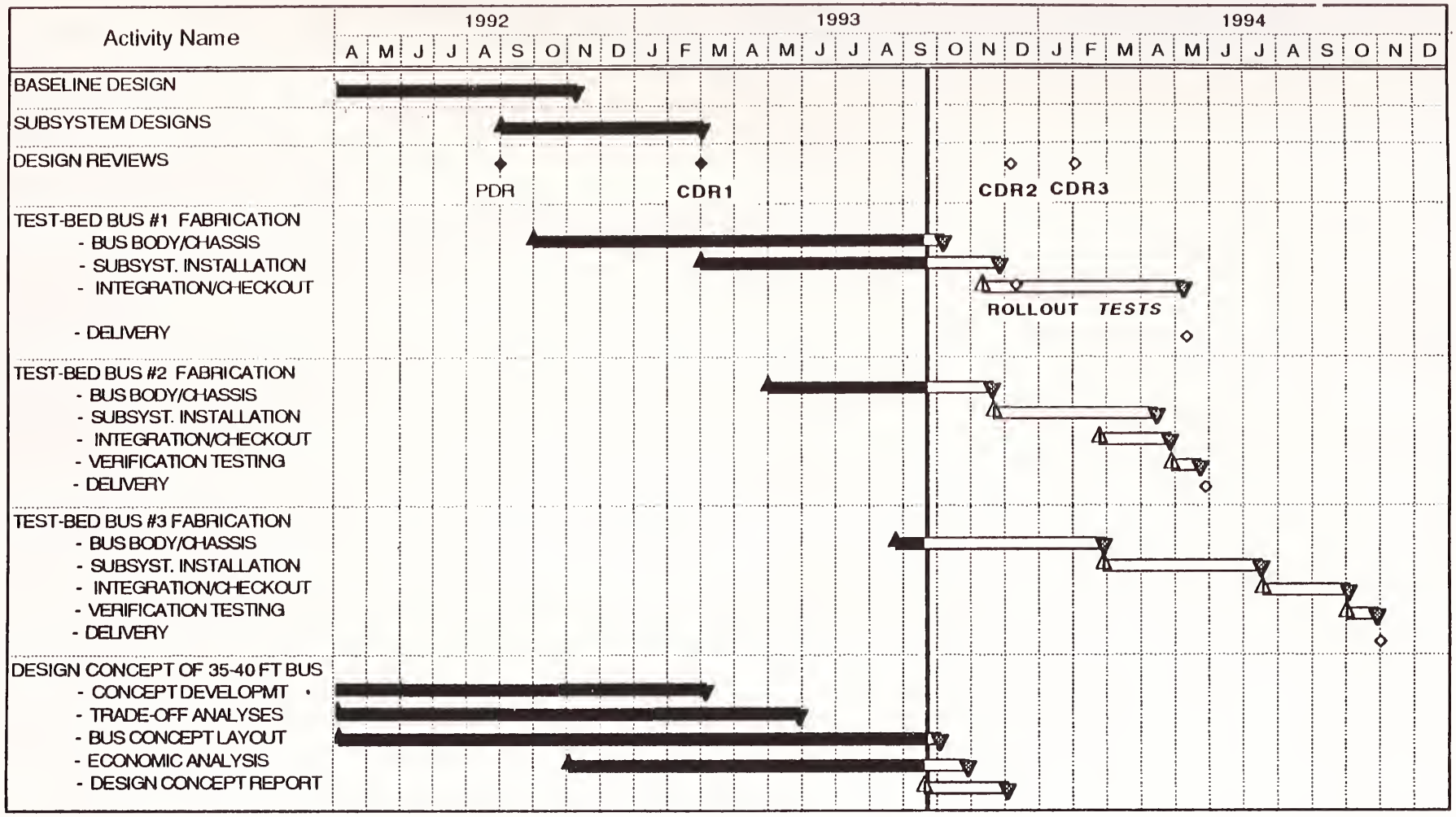


Liquid-cooled phosphoric acid
fuel cell subsystem.

CHART 3 Bus Design Characteristics

	Fuel Cell Bus	Diesel Bus
Size	27 ft, 22 seat	28 ft, 24 seat
Weight	19,025 lbs	17,000 lbs
Acceleration		
0-20 mph	6 sec	10 sec
0-40 mph	22 sec	34 sec
Fuel Energy Consumption (% of Diesel)	65	100

PROJECT SCHEDULE



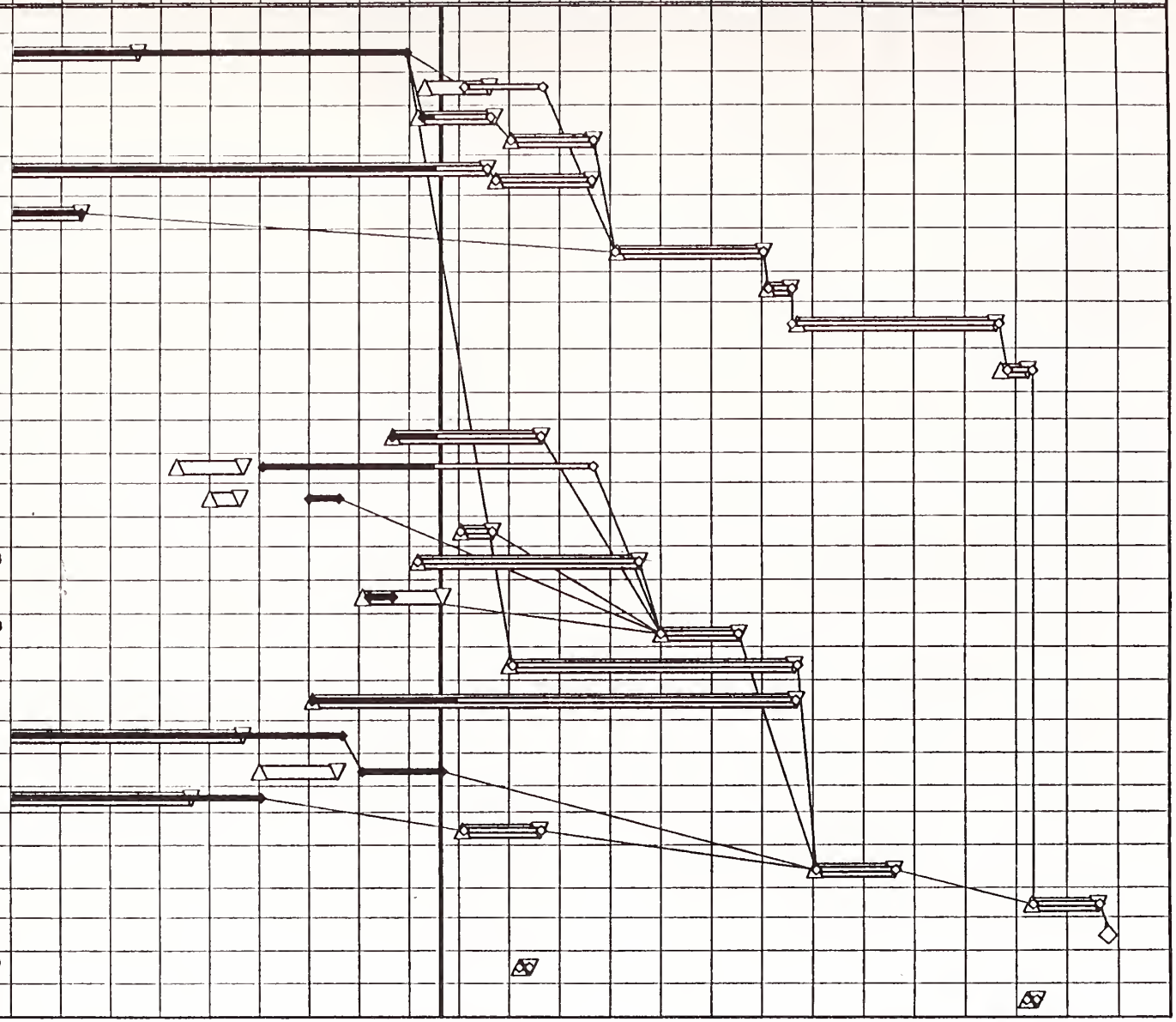
Sept 22 1993

CHART 4

TBB-1 Integration Schedule

Rev. No. 8: Sept 17, 1993

Activity Name	Projected Start Date	Projected Finish Date
Fuel Cell Subsyst (FCS)		
Aux Power Supply (APS) Fabrication and Test	Sun, Apr 04	Sun, Sept 12
PAC Test (w/o Stack)	Mon, Sept 20	Fri, Oct 01
Soleq Up-Chopper Fabrication Test	Tues, Sept 14 Mon, Sept 27	Fri, Sept 24 Fri, Oct 08
HPC Up-Chopper Fab. ***Test***	Mon, Jul 12 Sat, Sept 25	Fri, Sept 24 Fri, Oct 08
Stack Fabrication /Test	Mon, Mar 08	Wed, Jul 28
Subsyt Integration/ checkout/ adjustments	Mon, Oct 11	Mon, Nov 01
Fuel Cell Acceptance Test	Mon, Nov 01	Fri, Nov 05
FCS Packaging & Shipment to BMI	Fri, Nov 05	Fri, Dec 03
FCS Uncrating & Inspection at BMI	Sat, Dec 04	Wed, Dec 08
TBB Integration		
Fabricate/Install HVDU	Fri, Sept 10	Fri, Oct 01
TBB-1 High Volt Wiring	Mon, Aug 23	Fri, Oct 08
Install Interim 8D Batt	Mon, Aug 30	Fri, Sept 03
Install HVAC	Mon, Sept 20	Fri, Sept 24
Fabricate LVPS	Tues, Sept 14	Thurs, Oct 14
Install/checkout SCS	Tues, Sept 07	Fri, Sept 10
Accessory checkout	Mon, Oct 18	Thurs, Oct 28
Fabricate Motor Controller	Mon, Sept 27	Fri, Nov 05
Fabricate IGBT Motor ***Controller***	Mon, Aug 30	Fri, Nov 05
Set up Dynamometer	Tues, Jun 15	Fri, Sept 03
Dyno Calibration/check	Mon, Sept 06	Fri, Sept 17
NI/Cd Batt. Fab. & Deliv.	Mon, Apr 12	Mon, Aug 23
Install/ready NI/Cd Batt.	Mon, Sept 20	Fri, Oct 01
TBB-1 Dyno Testing with NI/Cd Battery (w/o FCS)	Mon, Nov 08	Fri, Nov 19
FCS Integration Into TBB-1	Wed, Dec 08	Fri, Dec 17
TBB-1 Rollout	Sat, Dec 18	
QWM-5	Tues, Sept 28	Wed, Sept 29
QWM-6	Tues, Dec 07	Wed, Dec 08



Key: ◇ Projected Start / End Date
△ Planned Start Date
▽ Planned End Date

Italics = Back-up componen

Sept 17, 1993

TBB-1 Delivery: 5/10/94
TBB-2 Delivery: 5/31/94
TBB-3 Delivery: 10/31/94

Prepared: Aug 6, 1993

CHART 5

CHART 6
TEST-BED BUS CONFIGURATION

Length	29 ft. (8.84 m)
Width	96 in. (244 cm)
Height	121 in. (306 cm)
Curb Weight	24,000 lb (10,880 kg)
Seating Capacity	25 passengers + driver
Standees	13
Physically Impaired	2 wheelchair locations and wheelchair lift
Wheelbase	195 in. (495 cm)
Floor Height	32 in. (81 cm)
Ground Clearance	10 in. (25 cm) minimum
Useful life	12-15 years
Operating Temp. Range	- 5.8°F to 131°F
Range	150 miles (241 km)

PHOSPHORIC ACID FUEL CELL SYSTEM

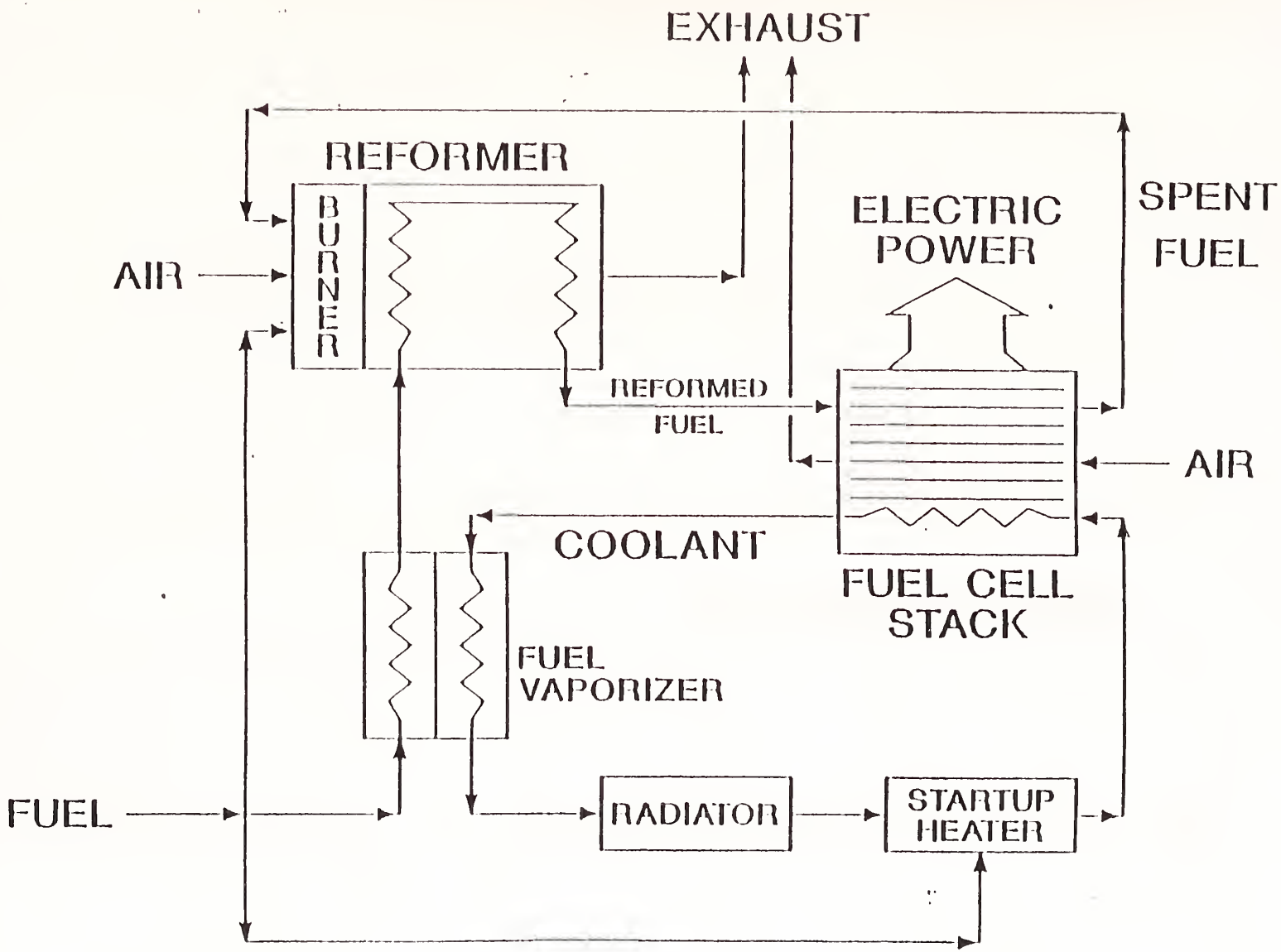
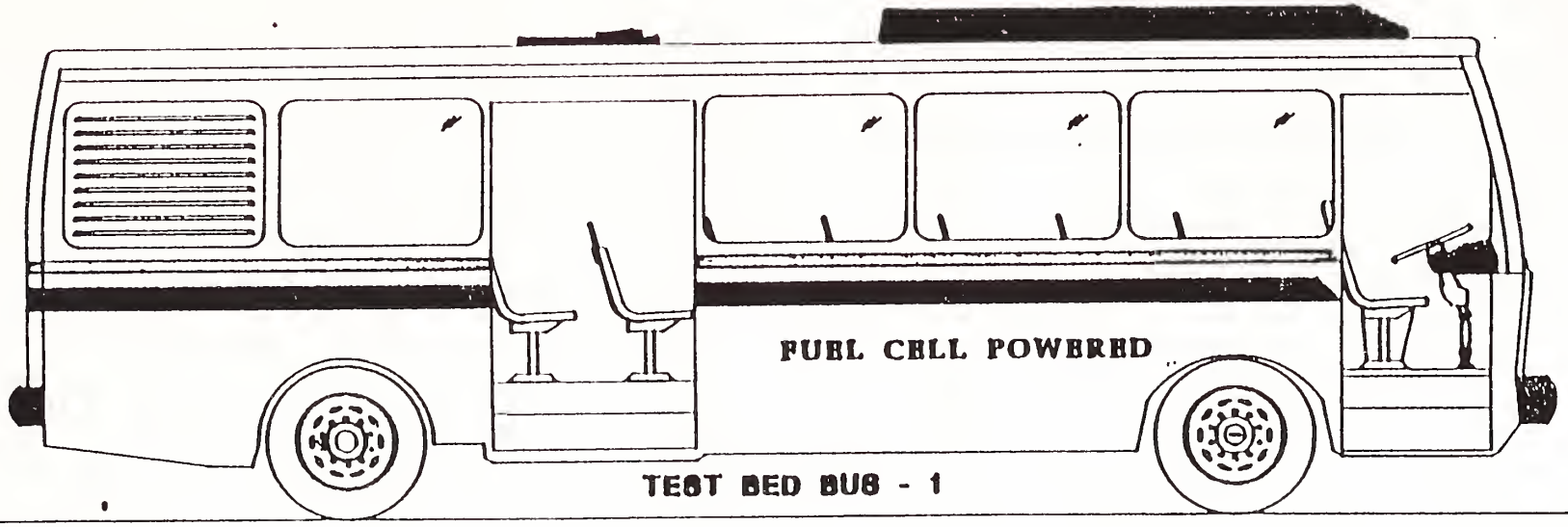


CHART 7

PERFORMANCE

SPEED	WHITE BOOK	PROJECTED
0-10 MPH	5.6 SEC	3.6 SEC
0-30 MPH	19 SEC	14.4 SEC
0-50 MPH	60 SEC	45.5 SEC
TOP SPEED	55 MPH	58 MPH
2.5% GRADE	44 MPH	44 MPH
12% GRADE	7 MPH	15 MPH
RANGE	150 MILES	150+ MILES



TEST BED BUS - 1

CHART 10
PRODUCT IMPROVEMENTS

- FUEL CELL SUBSYSTEM
  - REDUCE WEIGHT
  - REDUCE START-UP TIME
  - IMPROVE TRANSIENT RESPONSE
  - REDUCE REFORMER SIZE AND WEIGHT
  - INCORPORATE WATER RECOVERY
  - SIMPLIFY ACCESSORIES
  - IMPROVE EFFICIENCY FURTHER

- BATTERY
  - DEVELOP LIGHT-WEIGHT BATTERY FOR HYBRID APPLICATION

- BUS DESIGN
  - REDUCE BODY / CHASSIS WEIGHT
  - HEAT-ACTIVATED AIR-CONDITIONING
  - POSSIBLE LOW-FLOOR DESIGN

- ELECTRICAL SYSTEM
  - INTEGRATE ACCESSORIES WITH ELECTRICAL SYSTEM
  - INTEGRATE SYSTEM CONTROLLER WITH FUEL CELL CONTROLS AND POWER SUPPLIES

Fuel Cell Bus Program Funding Summary

Fiscal Year	DOT Funds	DOE Funds	SCAQMD Funds	FY Total Funds
FY 1987	$800,000	$1,000,000	$0	$1,800,000
FY 1988	800,000	1,600,000	0	2,400,000
FY 1989	900,000	2,000,000	300,000	3,200,000
FY 1990	847,000	2,000,000	600,000	3,447,000
FY 1991	1,000,000	2,000,000	0	3,000,000
FY 1992	900,000	2,000,000	800,000	3,700,000
FY 1993	1,800,000	2,000,000	370,000	4,170,000
Totals	$7,047,000	$12,600,000	$2,070,000	$21,717,000

Fuel Cell Bus Program Costs Summary

Phase I (FY87-FY90)	DOT Funds	DOE Funds	SCAQMD Funds	Total Funds
Booz, Allen & Hamilton - develop bus design - build and test half-scale fuel cell/battery power source	$760,000	$1,277,000	$150,000	$2,187,000
Energy Research Corporation - develop bus design - build and test half-scale fuel cell/battery power source	$760,000	$1,268,700	$150,000	$2,178,700
Georgetown University (7/87-3/90) - project management	$980,000	-	-	$980,000
Argonne National Lab (7/87-3/90) - project management	-	$965,000	-	$965,000
Phase I totals	$2,500,000	$3,511,000	$300,000	$6,311,000
Phase II (FY91-FY94)				
H-Power Corp. (through 9/93) - develop detailed bus design - fabricate 3 fuel cell buses	$1,976,000	$6,395,000	$1,770,000	$10,141,000
Georgetown Univ. (4/90-9/93) - project management	$2,571,000	-	-	$2,571,000
Argonne National Lab (4/90-9/93) - bus battery testing - project management	-	$1,804,000	-	$1,804,000
Other DOE Contractors (NREL,ESM,etc.) - environmental/infrastructure studies	-	$890,000	-	$890,000
Phase II (costs + commitments thru 9/93)	$4,547,000	$9,089,000	$1,770,000	$15,406,000
Total Program: Phases I & II (costs + commitments thru 9/93)	**$7,047,000**	**$12,600,000**	**$2,070,000**	**$21,717,000**

- 9/21/93

Break-down of H-Power Corp. Costs by Subcontractors

Funds committed as of 9/93:

H Power	$2,975,833
TMC	$1,033,000
BMI	$1,326,700
Fujl	$2,878,100
Soleq	$894,100
Booz,Allen	$858,800
Tecogen	$174,600
Total	$10,141,133

FUEL CELL / BATTERY POWERED BUS SYSTEM PROGRAM

PROGRAM OBJECTIVES

- To develop, evaluate, and show feasibility of a methanol-fueled phosphoric acid fuel cell/battery technology aimed at proof-of-concept via small urban test-bed bus.

- To advance the fuel cell/battery and control technologies in an integrated fashion with available power traiin technology through a test-bed for small urban bus applications.

- To show the technology viability/maturity for small bus application via field testing in a fleet operation so as to provide data for industry to make quality decisions for commercial product development.

- To advance the technology for urban transit so as to provide an alternative for diesel-powered full-size buses.

DOE FUEL CELL/BATTERY POWERED BUS PROGRAM

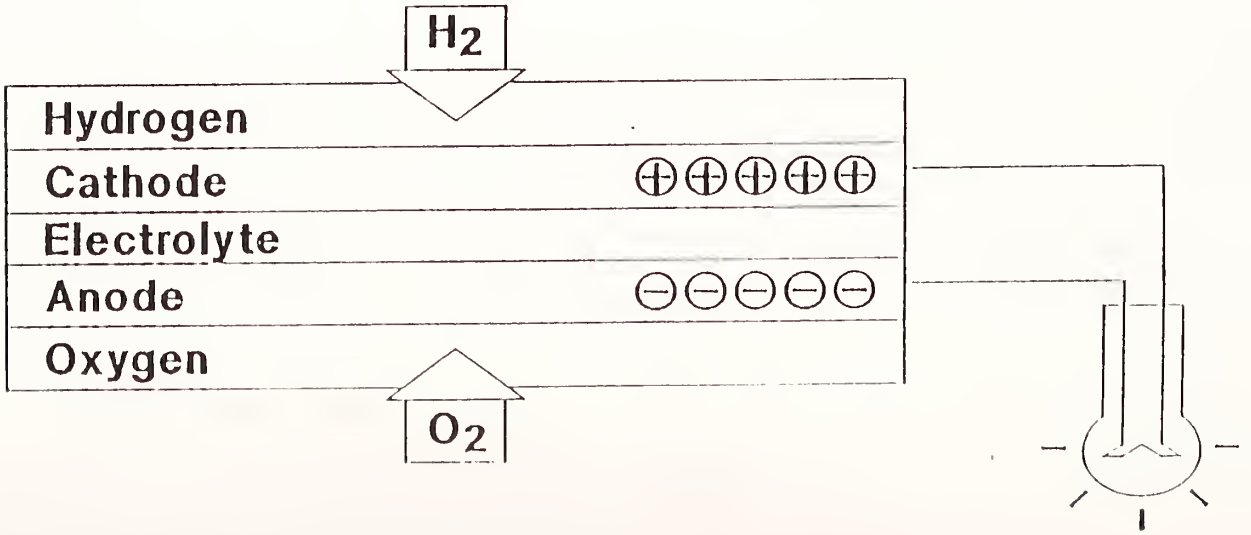
The Fuel Cell/Battery Bus is being developed as an alternative to the diesel powered urban transit bus.

The benefits:

- Air Quality - Fuel Cell virtually eliminates particulates, NOx and sulfur oxide emissions and significantly reduces hydrocarbons and CO
- Fuel Flexibility - Utilizes non-petroleum based fuels
- Fuel Economy - Fuel Cell energy efficiency is greater than comparable diesel or internal combustion of methanol
- Quiet Operation - Noise level is dramatically reduced

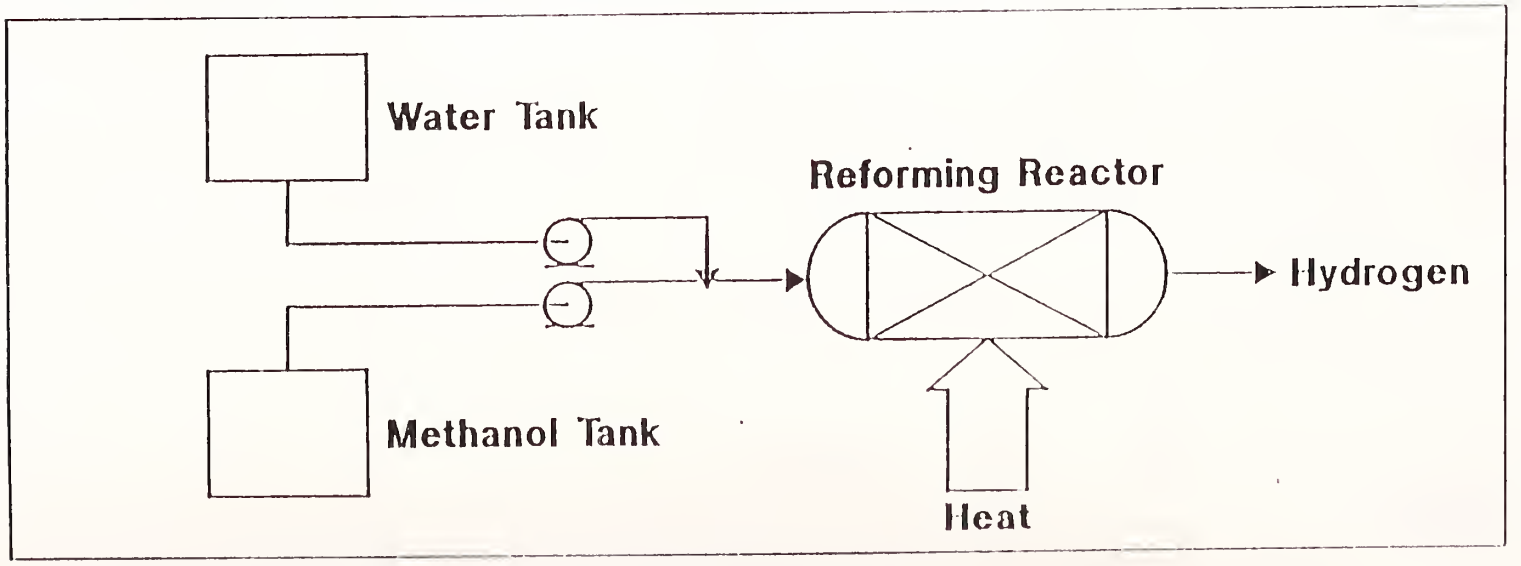
What Is A Fuel Cell?

- Hydrogen and oxygen are electrochemically combined to water at low temperature, releasing up to 90% of the chemical energy as electricity.
- A fuel cell operates quietly, has no moving parts, and is non–polluting

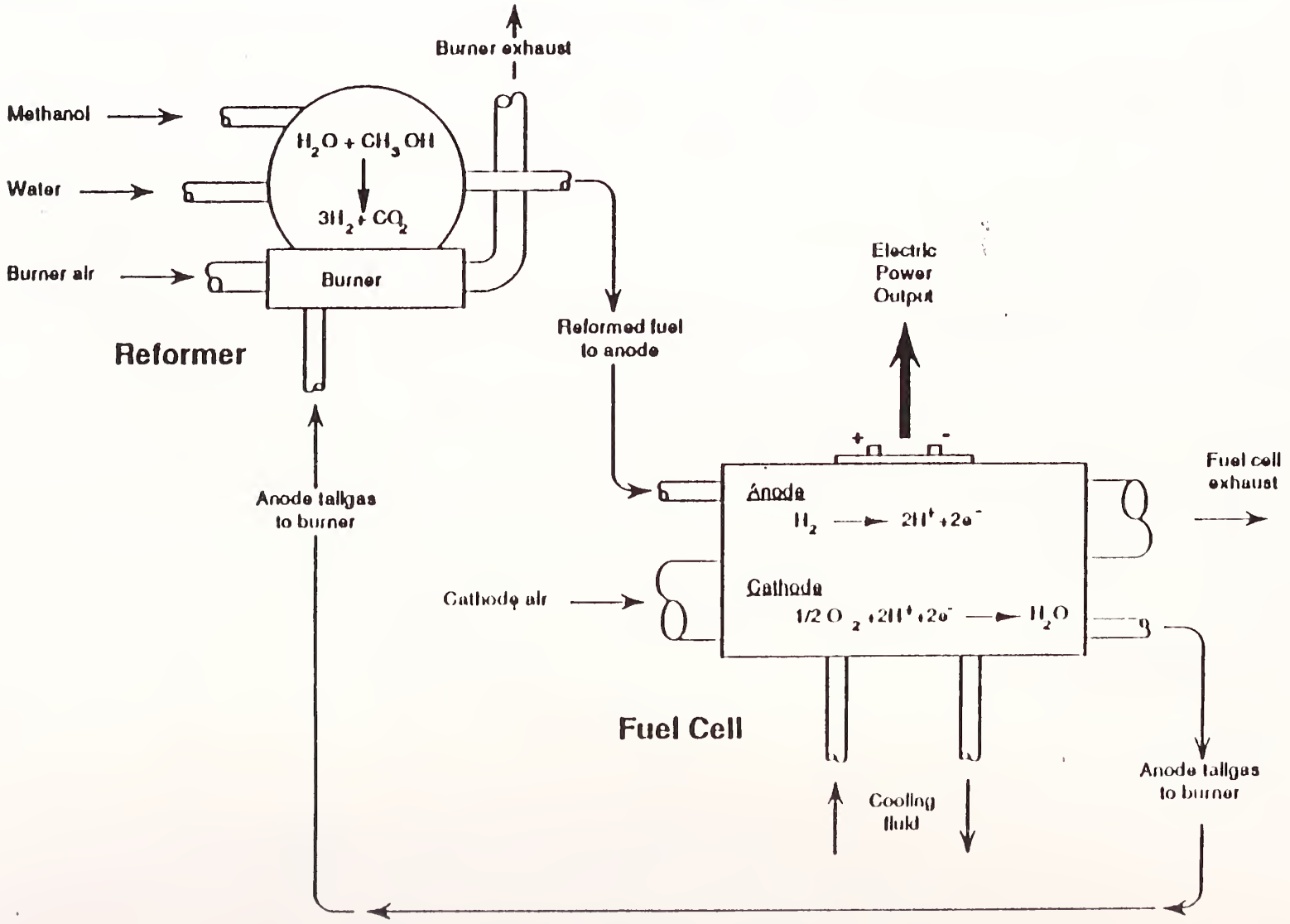


How Is The Hydrogen Obtained?

- Today's fuel cells cannot operate directly on methanol. The methanol must be reacted with water in a "reforming reactor" using heat to drive the reaction:
  $CH_3OH + H_2O \rightarrow 3H_2 + CO_2$
- The temperature in the reforming reactor must be controlled at about 200°C (390°F)
- The heat source is the depleted fuel leaving the fuel cell

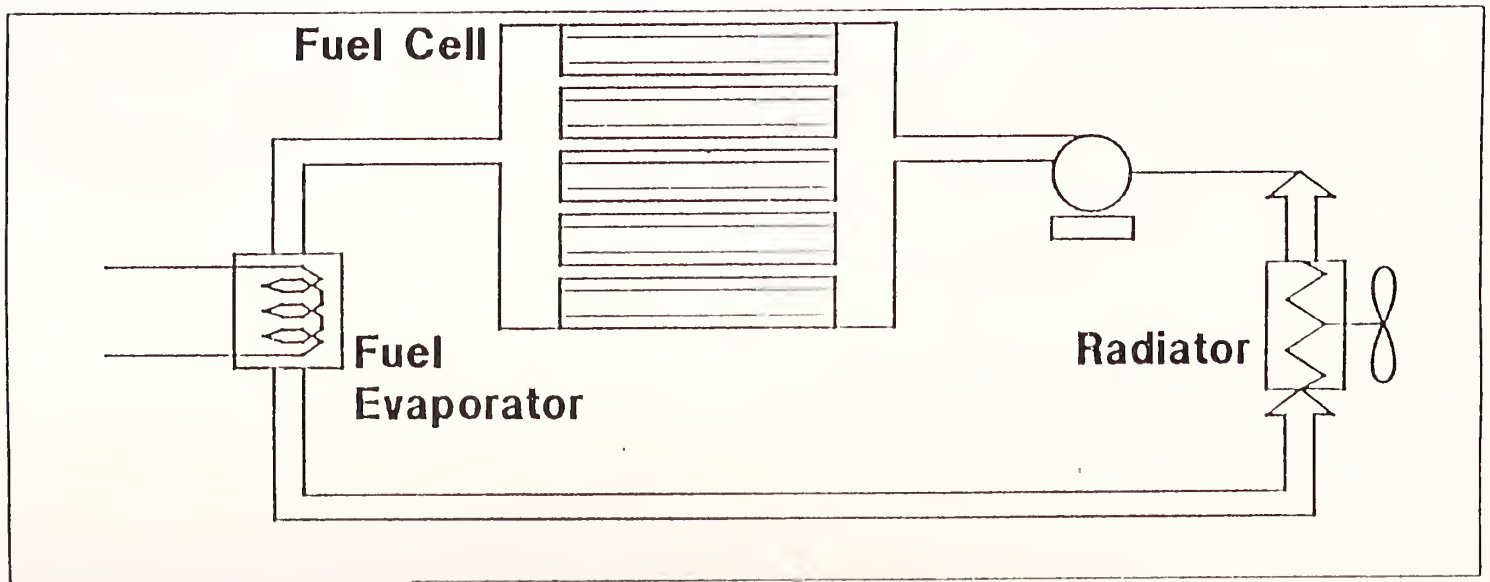


SCHEMATIC OF A FUEL CELL SYSTEM

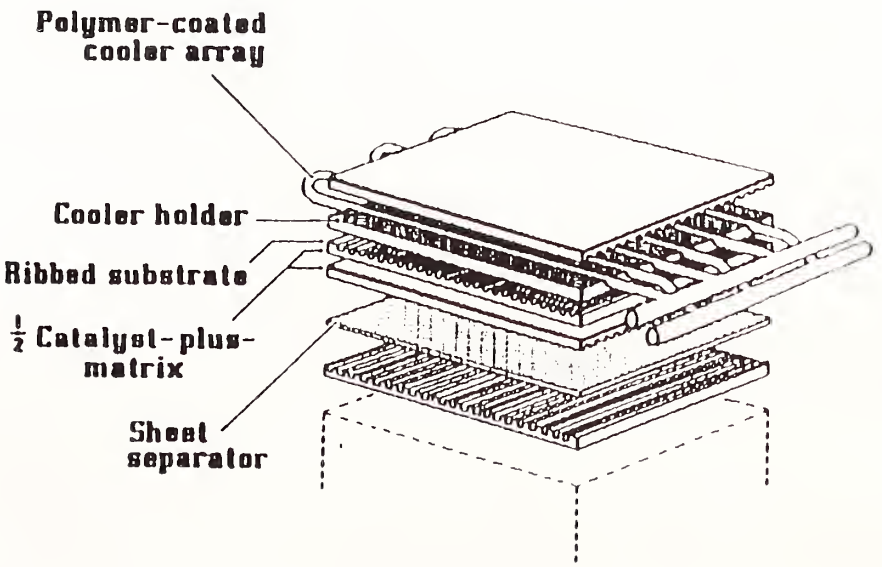


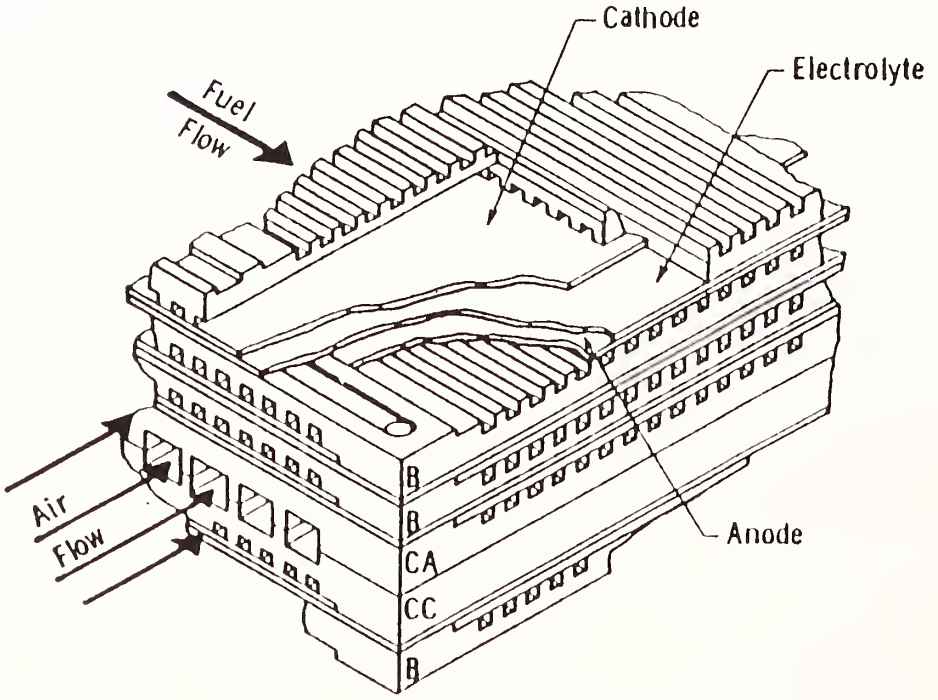
How Is The Operating Temperature Of The Fuel Cell Maintained?

- Fuel cells generate excess heat, which must be removed by cooling. The amount of the excess heat is roughly equivalent to the power output.
- Phosphoric acid fuel cells can be cooled by:
  - Steam/water
  - Mineral oil
  - Air
- In liquid–cooled cells the heat is released to the environment through a radiator. In air–cooled cells the hot air is released directly.



COOLING METHODS FOR FUEL CELLS





B - Bipolar plate with process air & fuel channels

CA - Anode DIGAS cooling plate

CC - Cathode DIGAS cooling plate

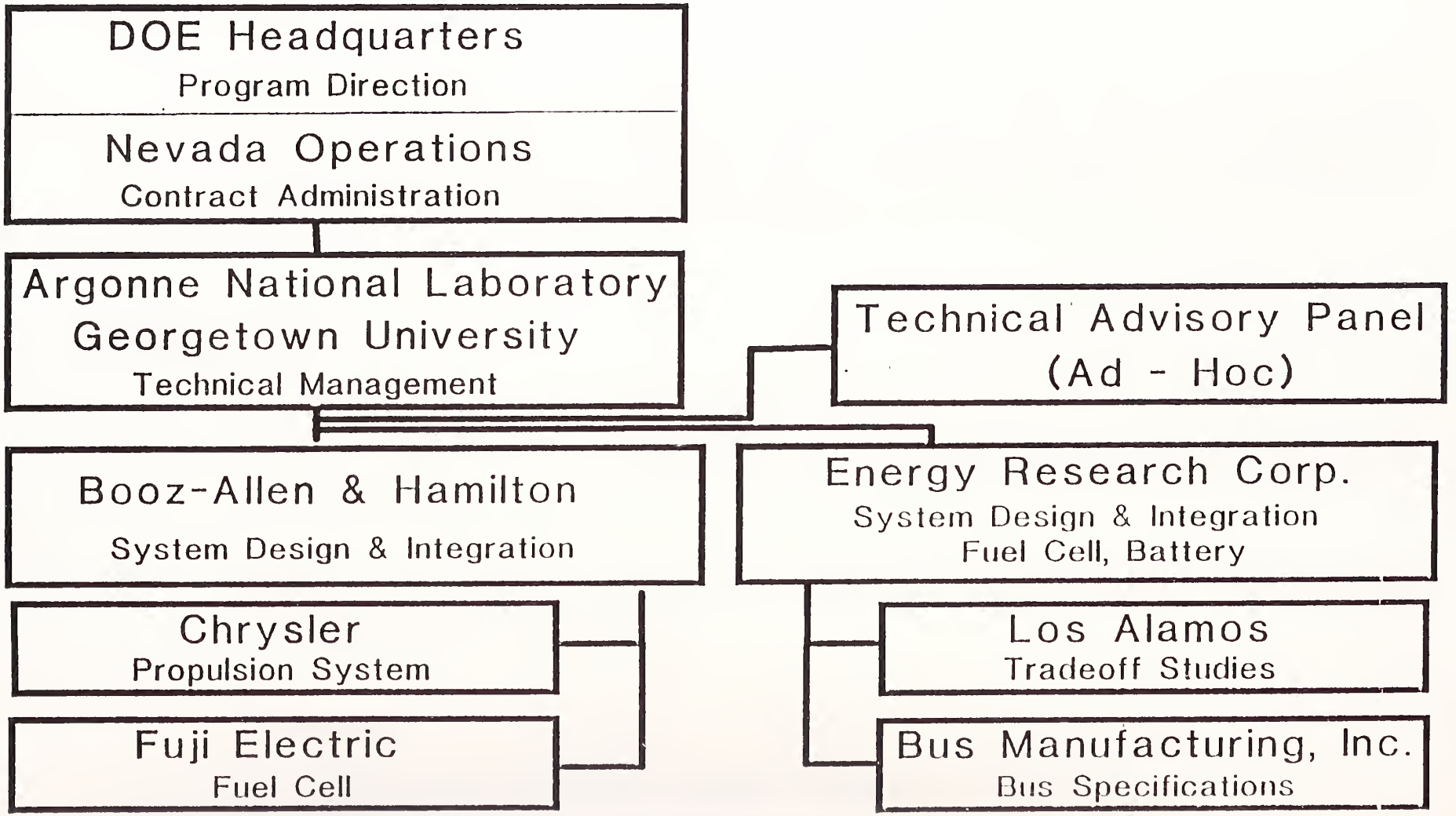
FUEL CELL/BATTERY POWERED BUS PROGRAM

- **Urban Transit Bus Selected As The Entry Point For Application Of Fuel Cells To Transportation**

  - Operation in the inner city will accentuate the environmental compatability of the fuel cell power system
  - The transit route structure is relatively fixed and permits evaluation under controlled conditions
  - The transit industry has an infrastructure in place to support operation & evaluation
  - The long service life of transit buses allows amortization of the initial higher acquisition cost over a reasonable time period
  - The bus size permits accommodation of the first generation fuel cell designs

Fuel Cell Powered Bus Program

Program Organization Phase I

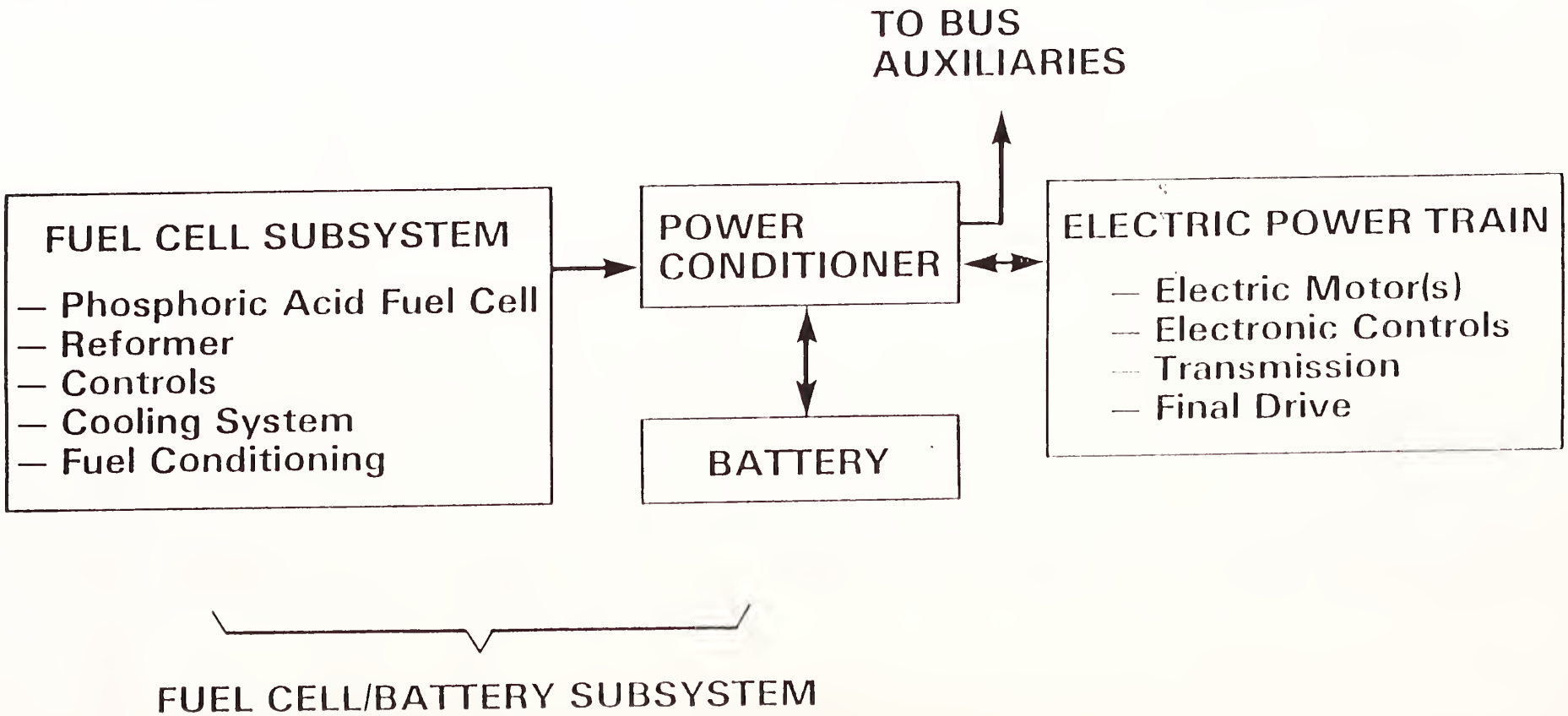


PHASE I

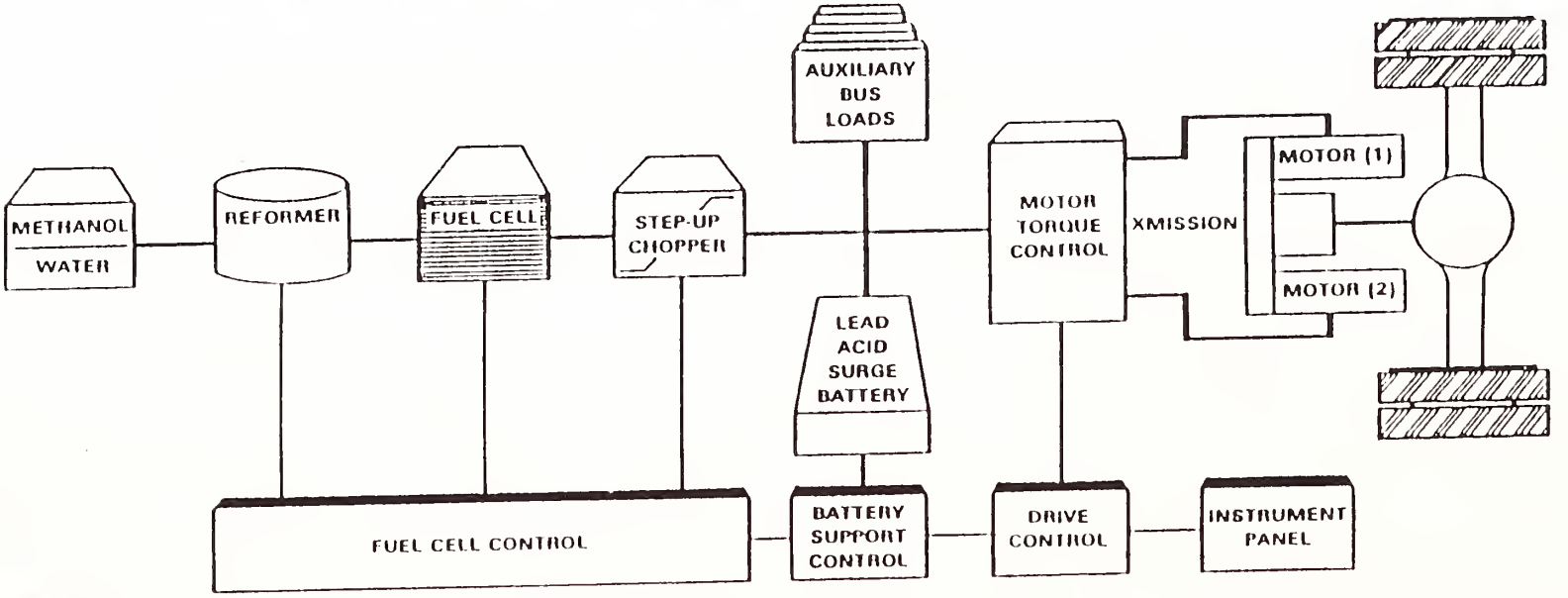
- OBJECTIVE
  - To develop, evaluate and show the feasibility of a methanol-fueled phosphoric acid fuel cell/battery power source for an urban transit bus

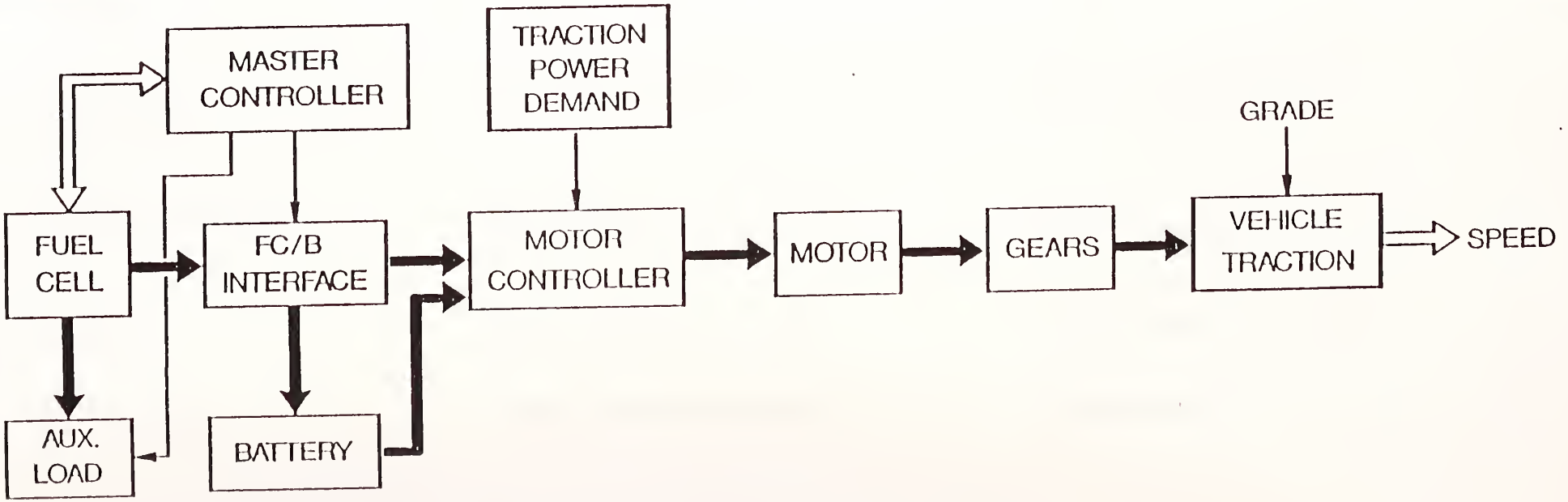
- APPROACH
  - Primarily directed at the development of the fuel cell subsystem
  - Utilize available batteries, motors, controllers, drivetrain components, and buses
  - Evaluated in the context of an overall bus design
    - -- Thru overall bus system design and analyses
    - -- Confirmed by brassboard evaluation

BUS PROPULSION SUBSYSTEM BLOCK DIAGRAM



BUS SYSTEM BLOCK DIAGRAM





COMPARISON OF BUS DESIGNS

	BAH	ERC
Size	27-ft	27-ft
Weight	19,030 lbs	19,000 lbs
Seats	20	20
FC/Battery Interface	step-up chopper	direct coupling with current limiter
Power Source	liq-cooled 50-kW PAFC lead-acid battery	air-cooled 56-kW PAFC Ni-Cd battery
Motor	3500 RPM, DC motor	3200 RPM, DC motor
Drivetrain	2-speed transmission	2-speed axle

PERFORMANCE COMPARISONS

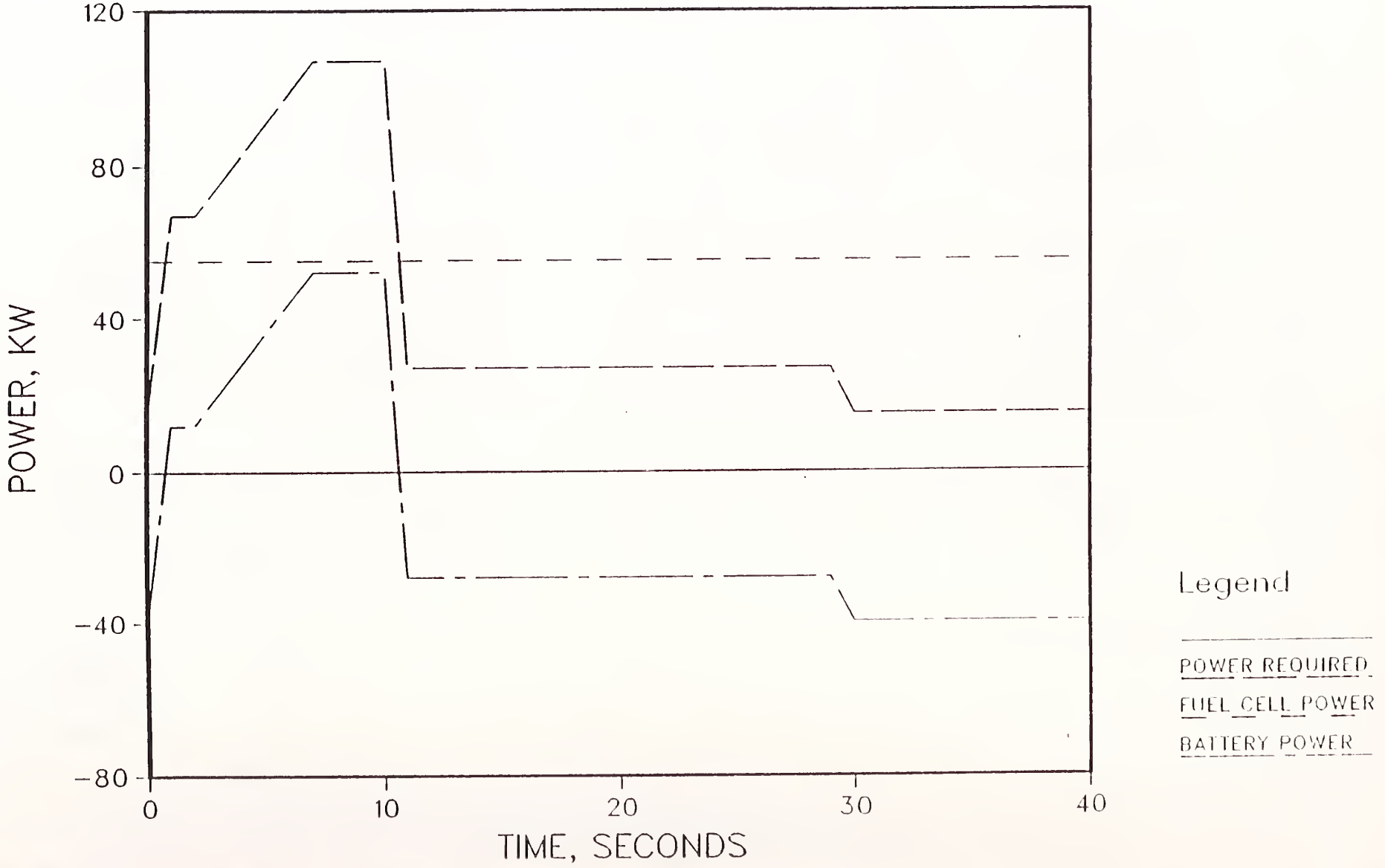
	BAH	ERC	Diesel
Acceleration			
0-20 mph (sec)	6	10	10
0-40 mph (sec)	22	33	34
GU Route Time (min)	30.3	31.3	31.7
Fuel Energy Consumption (% of Diesel)	65	89	100

BRASSBOARD SYSTEM DESCRIPTIONS

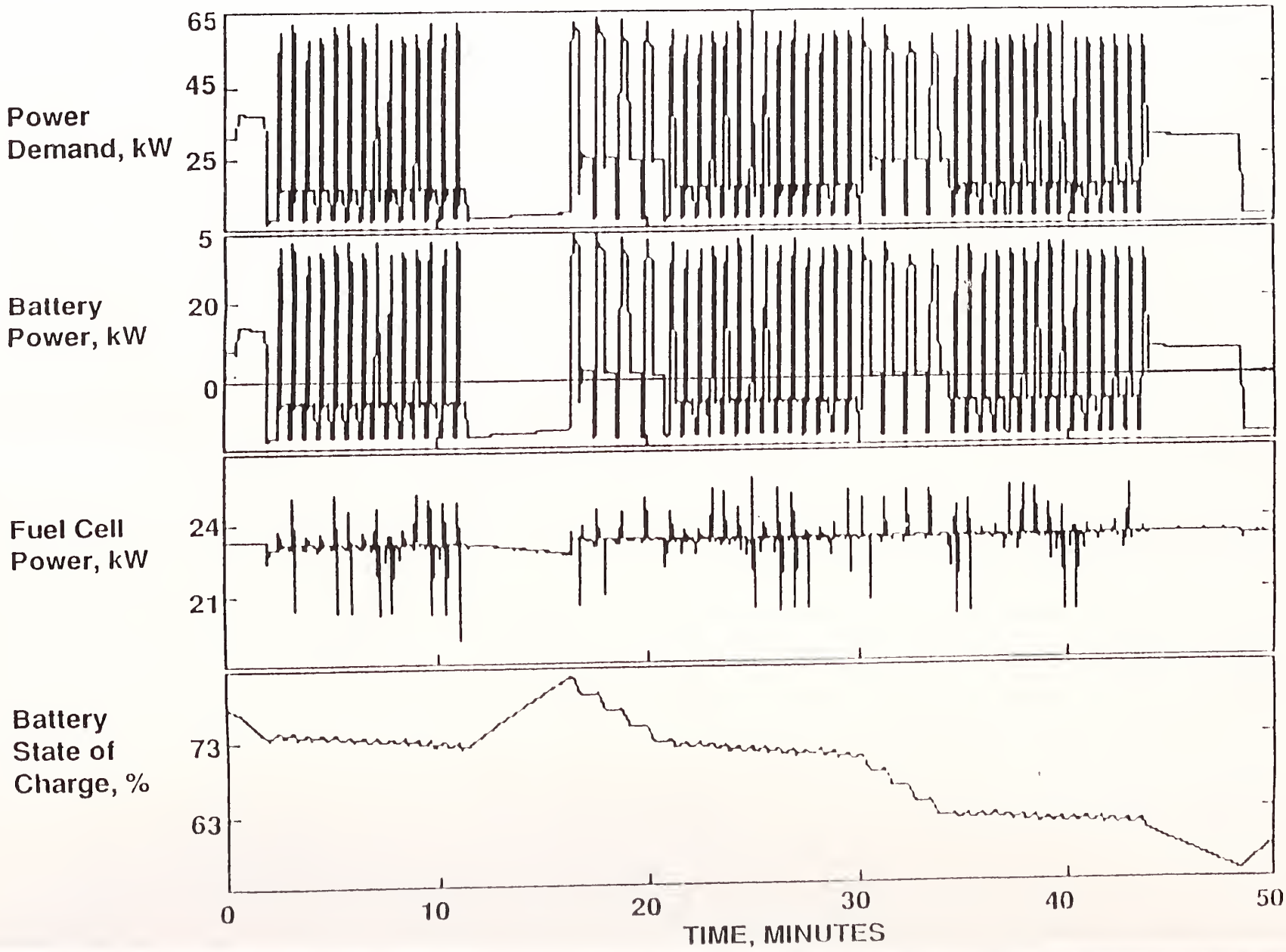
- Booz · Allen/Chrysler/Fuji Brassboard
  - 25-kW liquid-cooled fuel cell subsystem
  - 43-kW lead-acid battery
  - Step-up chopper
  - System controls

- ERC Brassboard
  - 32-kW air-cooled fuel cell subsystem
  - 36-kW nickel/cadmium battery
  - Fuel cell current limiter
  - System controls

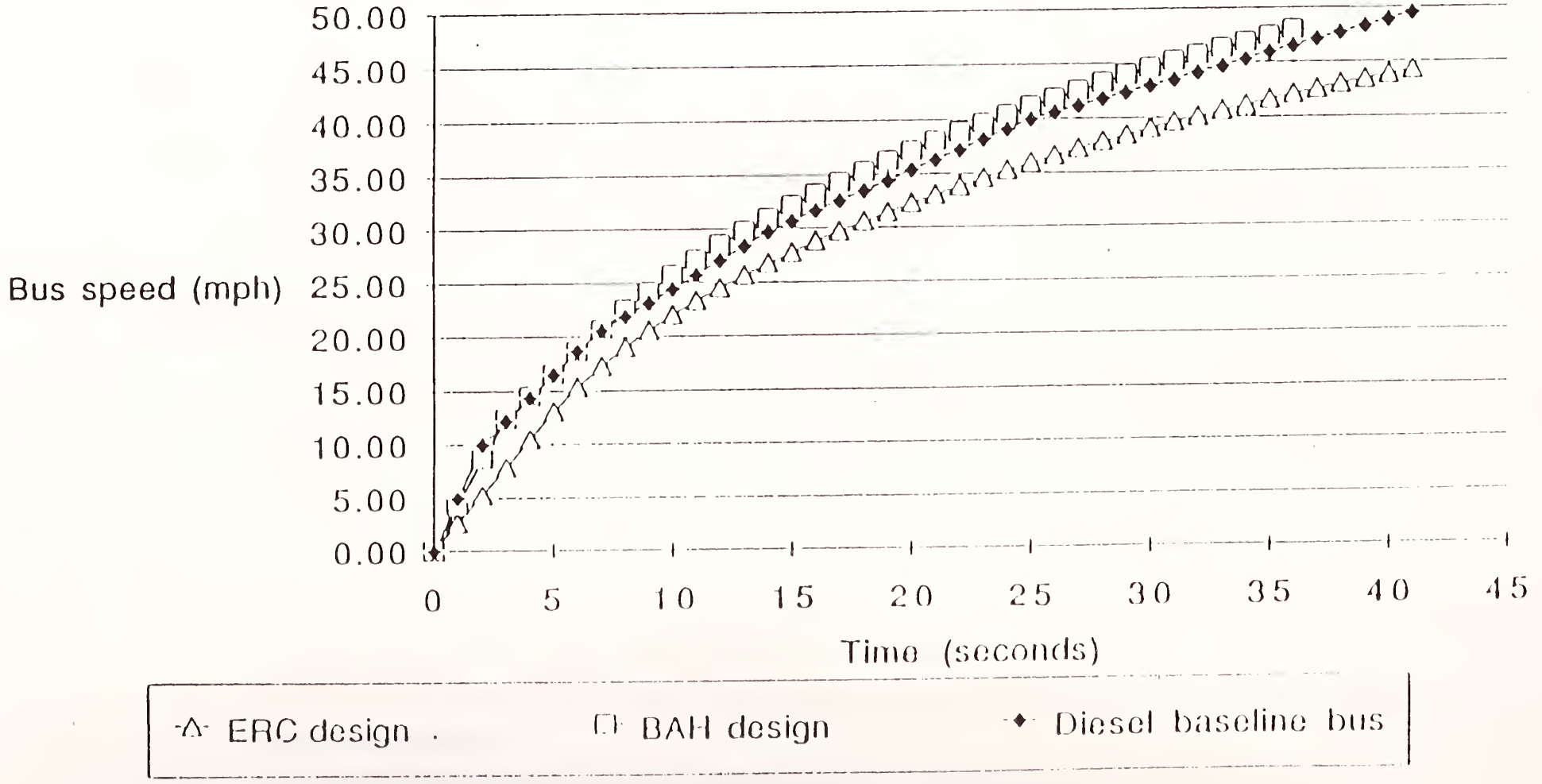
POWER REQUIREMENTS FOR FUEL CELL BUS ON CBD CYCLE



BRASSBOARD TEST DATA FOR DOT/UMTA COMPOSITE DRIVING CYCLE



FULL POWER ACCELERATION



BOOZ-ALLEN BRASSBOARD TEST RESULTS

- Fuel Cell Subsystem Met or Exceeded Performance Specifications
  - Power Output of 25.0 kW (vs. 25 kW spec.)
  - Methanol Consumption of 10.8 kg/h (vs. 11.3 kg/h spec.)

- Battery Performance Verification Completed
  - Battery current/voltage characteristics confirmed
  - Battery charge acceptance rate is lower than anticipated, but battery power capability is acceptable

- Fuel Cell/Battery System Tests Performed
  - Automatic operation of power sharing with battery verified
  - Fuel cell/battery system operated well from no load to full power (68-kW)
  - Ability to handle rapid load changes demonstrated

- Environmental Benefits were Confirmed
  - Noise was less than 78 dBA at 1 meter
  - Hydrocarbons (HC) and Nitrogen Oxides (NOX) emissions were undetectable
  - Carbon Monoxide (CO) emissions were less than 30 ppm

ERC BRASSBOARD TEST RESULTS

- Fuel Cell Subsystem Met or Exceeded Performance Specifications
  - Power Output of 32.2 kW Obtained (vs. 32 kW spec.)

- Battery Performance Verified
  - Power capability met specifications
  - Charge/discharge characteristics were confirmed

- Fuel Cell/Battery System Tests
  - Automatic operation of power sharing with battery verified
  - Fuel cell/battery system operated well over the full power range
  - Ability to handle rapid load changes demonstrated

- Environmental Benefits Were Confirmed
  - Nitrogen Oxides (NOx) emissions were undetectable (<1 ppm)
  - Carbon Monoxide (CO) emissions were undetectable (<10 ppm)

OPERATING CHARACTERISTICS

- Operates at 190 - 210 C.
- Consumes oxygen in the air and produces mainly water and CO_2.
- Small amount of NO_x is produced in the burner.
- Comparison of the exhaust gas from a fuel cell and a diesel bus: (g/bhp.hr)

	Diesel	Fuel Cell	Ratio
CO	15.5	Undetectable	~0
NO_x	5.0	0.023	0.0046
Hydrocarbon	1.3	0.000350	0.000276
Particulates	0.10	0.0000034	0.0000354

BRASSBOARD TEST RESULTS

- Both BAH and ERC systems met or exceeded design specifications
- No fundamental design problems uncovered
- Both systems successfully demonstrated the ability to handle rapid load changes encountered in typical bus operation
- Environmental benefits of low emissions and noise levels were confirmed

ECONOMIC COMPARISONS FOR 27-FT BUSES

	BAH	ERC	Diesel
Capital Cost (% of Diesel)	121	136	100
O&M Cost (% of Diesel)	66	66	100
Fuel Cost (% of Diesel)	65	89	100
Life Cycle Cost (% of Diesel)	83	97	100

PHASE I REPORTS

11/88 Conceptual Design Reports

- Provides baseline bus and propulsion system design information
- Allows initial feasibility assessment

06/89 Tradeoff Analysis Reports

- Provides optimized bus and propulsion system design plus economic projections
- Allows more accurate feasibility assessment

12/89 Phase I Proof-of-Feasibility Reports

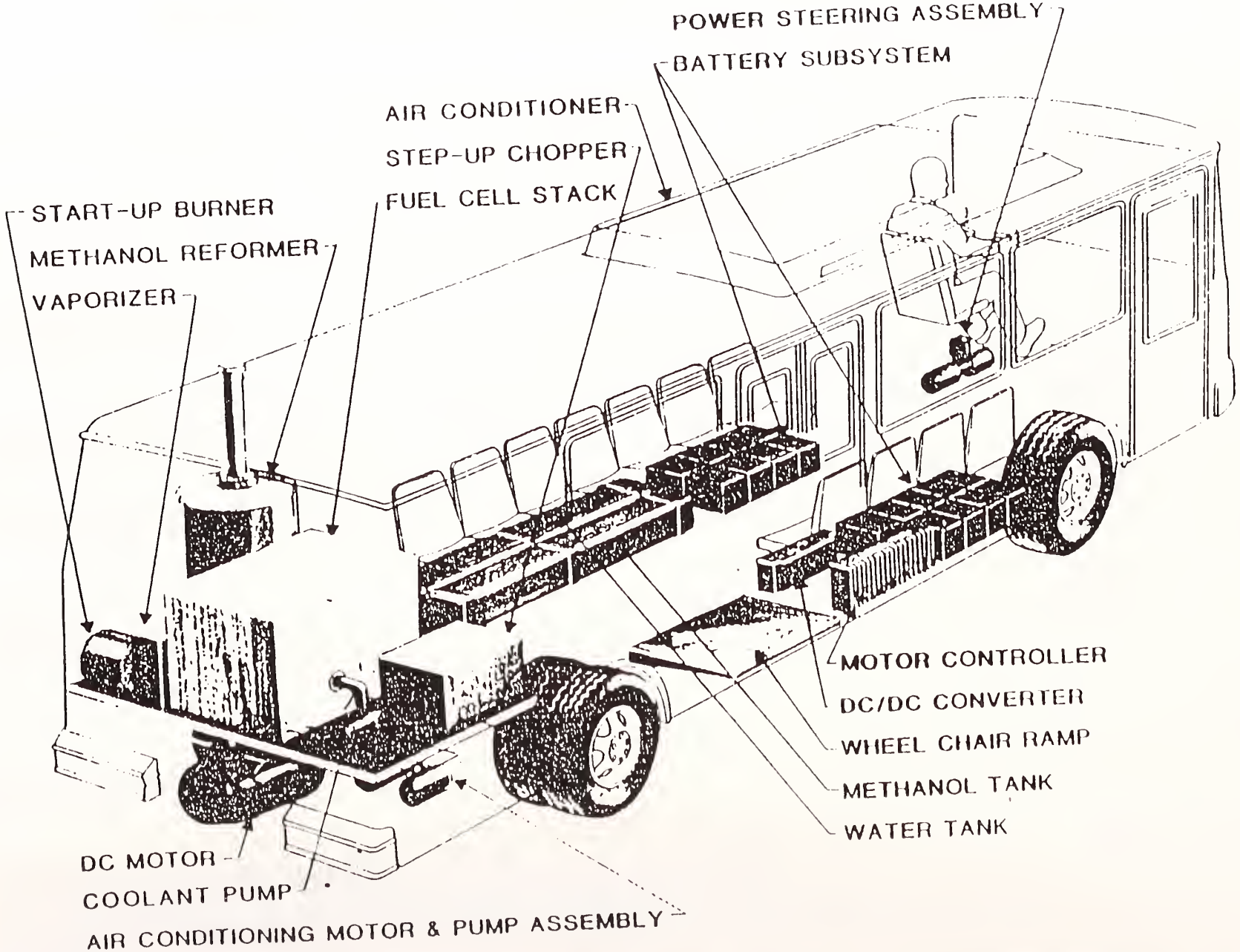
- Provides test results and all final Phase I data
- Allows final assessment of feasibility

PHASE I CONCLUSIONS

- A fuel cell/battery powered urban bus is technically feasible and practical
- The life cycle cost of the fuel cell/battery bus can be economically competetive
- "Quality of Service" improvements such as acceleration, low noise, low emissions offer additional undetermined economic benefits
- Design projections for the fuel cell/battery power source have been confirmed in brassboard tests

GO/NO - GO DECISION FOR PHASE II

- Phase I results show that a fuel cell/battery-powered urban bus is feasible
    - Technical Advisory Panel (ad hoc) corroborates this conclusion
- Project Management Team recommended to proceed to Phase II
- Funding agencies agree with the decision to proceed to Phase II


POWER STEERING ASSEMBLY
BATTERY SUBSYSTEM
AIR CONDITIONER
STEP-UP CHOPPER
FUEL CELL STACK
START-UP BURNER
METHANOL REFORMER
VAPORIZER
MOTOR CONTROLLER
DC/DC CONVERTER
WHEEL CHAIR RAMP
METHANOL TANK
WATER TANK
DC MOTOR
COOLANT PUMP
AIR CONDITIONING MOTOR & PUMP ASSEMBLY

FUEL CELL COMPARISONS

	Liquid Cooled	Air Cooled
Fuel Cell Stack		
Current density (mA/cm^2)	240	200
Volume (ft^3)	26	63
Weight (lb)	1360	1600
Fuel Cell System		
Efficiency (% HHV)	38	32

FUEL CELL STACK

CONSIDERATIONS

- largest component of propulsion system
- most difficult to package on bus
- volume affects room available for passengers
- highest cost component of propulsion system

TECHNICAL ASSESSMENT

Liquid-cooled fuel cell stack is superior

- volume is 60% smaller
- capital cost is inherently less
  - due to greater current density
- energy efficiency is 20% greater
  - greater recovery of waste heat
  - 50% lower cooling power required
- better reliability
  - shorter stack less sensitive to vibration
  - more mature technology (10,000 hours operation guaranteed for Phase II hardware)

FUEL REFORMER

CONSIDERATIONS

- occupies much less volume than fuel cell stack
- not inherently expensive component
- limits transient response capability of fuel cell system

TECHNICAL ASSESSMENT

- both ERC and BAH reformers perform well
  - 100% conversion of methanol to hydrogen
- both reformers are in early development stage
- ERC's reformer is smaller, has greater temperature stability, and is more efficient

FUEL CELL/BATTERY INTERFACE

TECHNICAL ASSESSMENT

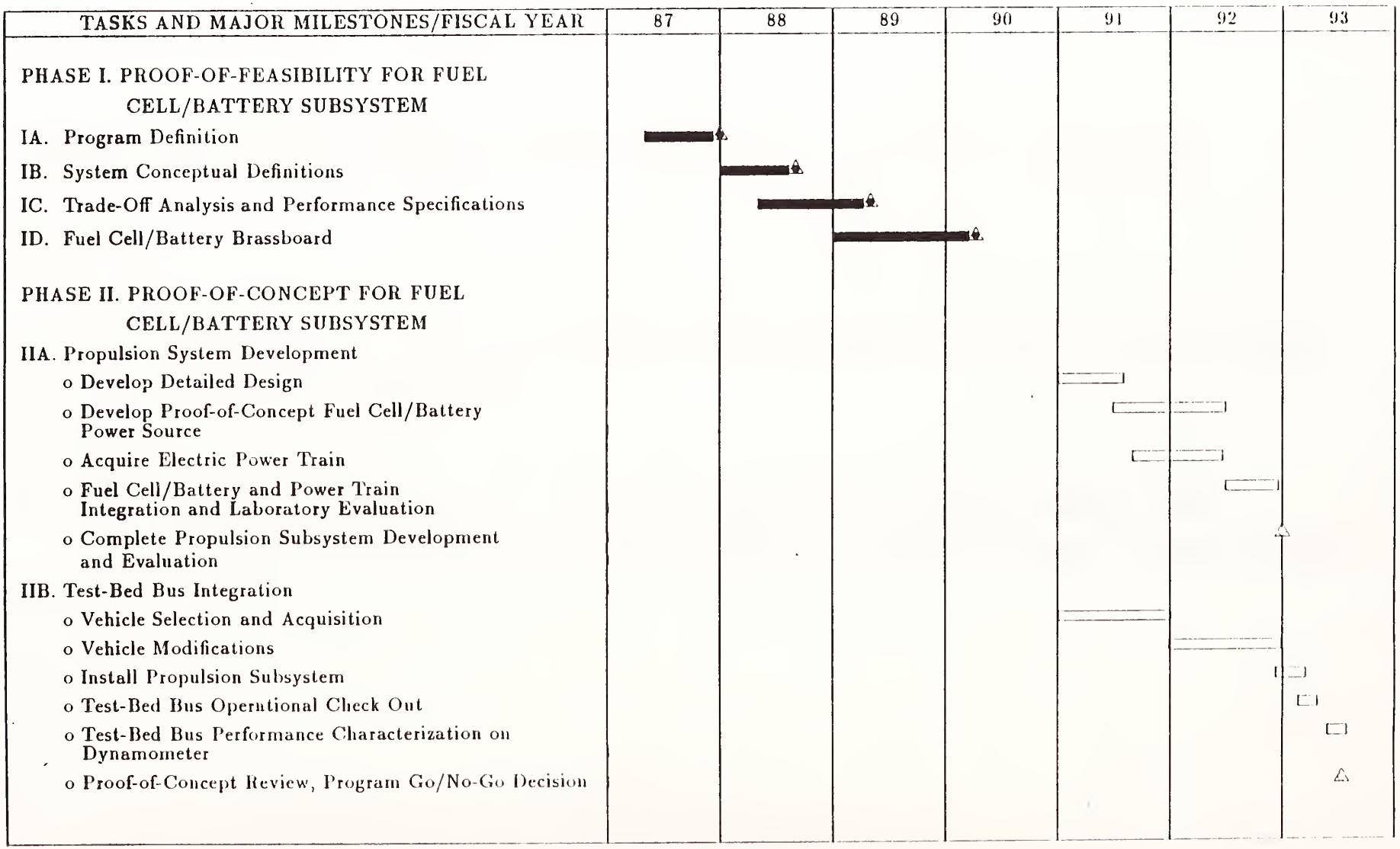
- BAH's step-up chopper
  - readily handles changes in fuel cell or battery
  - permits the use of shorter, more rugged stacks
  - provides lowest risk in terms of system performance

- ERC fuel cell current limiter
  - system performance sensitive to changes in fuel cell & battery
  - introduces additional losses in fuel cell and battery
    -- unknown impact on fuel cell and battery life

PROBLEMS AND ISSUES

- Fuel Cell System Start-up and Thermal Cycling
- Performance Decay
  - frequent thermal cycling
  - transients
  - vibrations
- Initial Cost and Life
- Battery Cycling Life

SCHEDULE - FUEL CELL/BATTERY POWERED BUS SYSTEM PROGRAM


TASKS AND MAJOR MILESTONES/FISCAL YEAR
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PHASE I. PROOF-OF-FEASIBILITY FOR FUEL CELL/BATTERY SUBSYSTEM
IA. Program Definition
IB. System Conceptual Definitions
IC. Trade-Off Analysis and Performance Specifications
ID. Fuel Cell/Battery Brassboard
PHASE II. PROOF-OF-CONCEPT FOR FUEL CELL/BATTERY SUBSYSTEM
IIA. Propulsion System Development
o Develop Detailed Design
o Develop Proof-of-Concept Fuel Cell/Battery Power Source
o Acquire Electric Power Train
o Fuel Cell/Battery and Power Train Integration and Laboratory Evaluation
o Complete Propulsion Subsystem Development and Evaluation
IIB. Test-Bed Bus Integration
o Vehicle Selection and Acquisition
o Vehicle Modifications
o Install Propulsion Subsystem
o Test-Bed Bus Operational Check Out
o Test-Bed Bus Performance Characterization on Dynamometer
o Proof-of-Concept Review, Program Go/No-Go Decision

CONCLUSION

The fuel cell/battery powered bus system program

- **Is a major forward step in the application of fuel cells in transportation**
- **Could provide a viable propulsion alternative for diesels which does not require a petroleum based fuel**

RESEARCH AND DEVELOPMENT OF PHOSPHORIC ACID FUEL CELL/BATTERY POWER SOURCE INTEGRATED IN A TEST-BED BUS

DOE Contract No. DE-ACO2-91CH10447

Sponsors:

- U.S. Department of Energy (DOE)
- U.S. Department of Transportation (DOT)
- South Coast Air Quality Management District (SCAQMD)

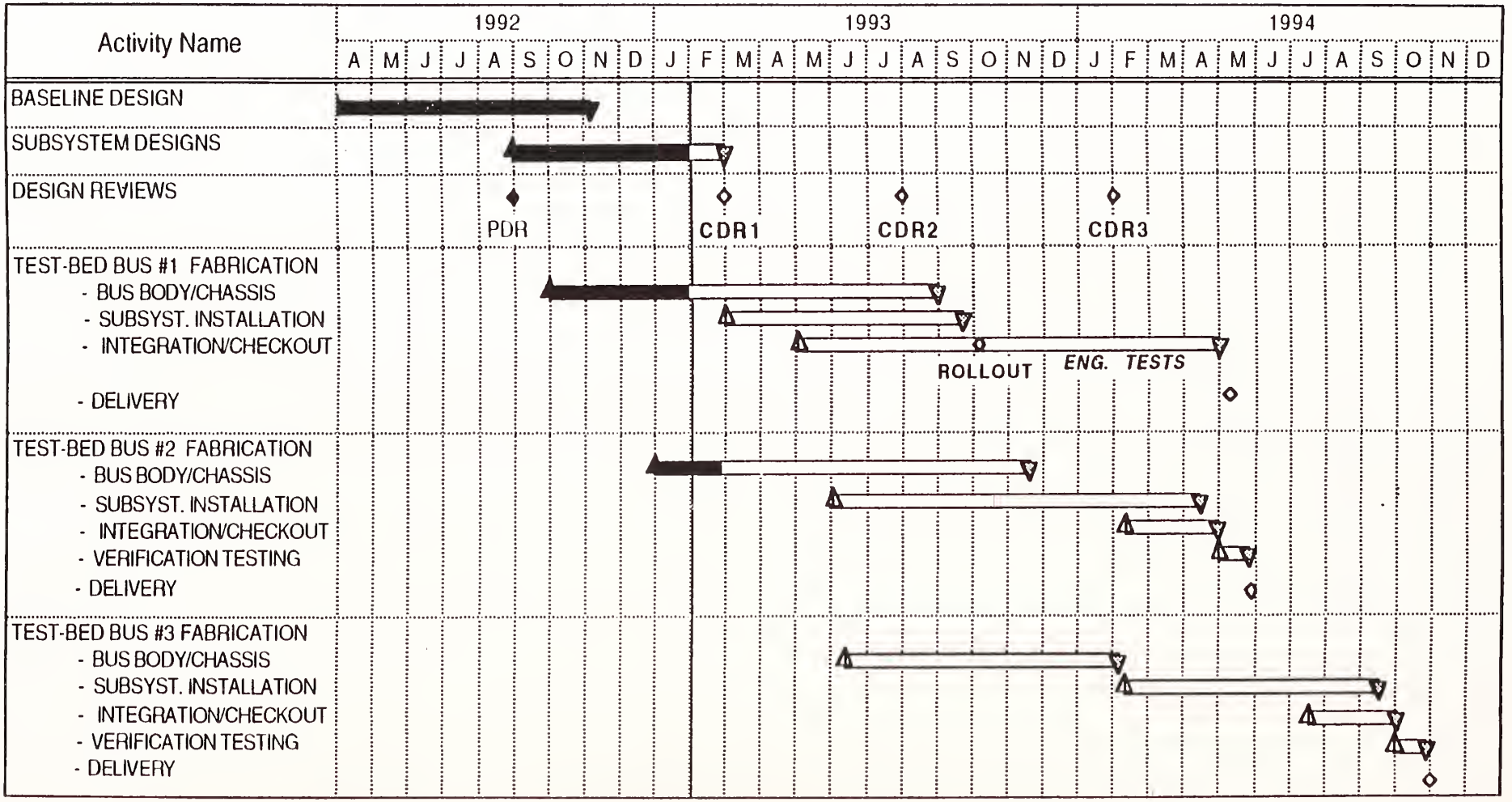
Project Management Team:

- DOE
- Argonne National Laboratory
- **Georgetown University**

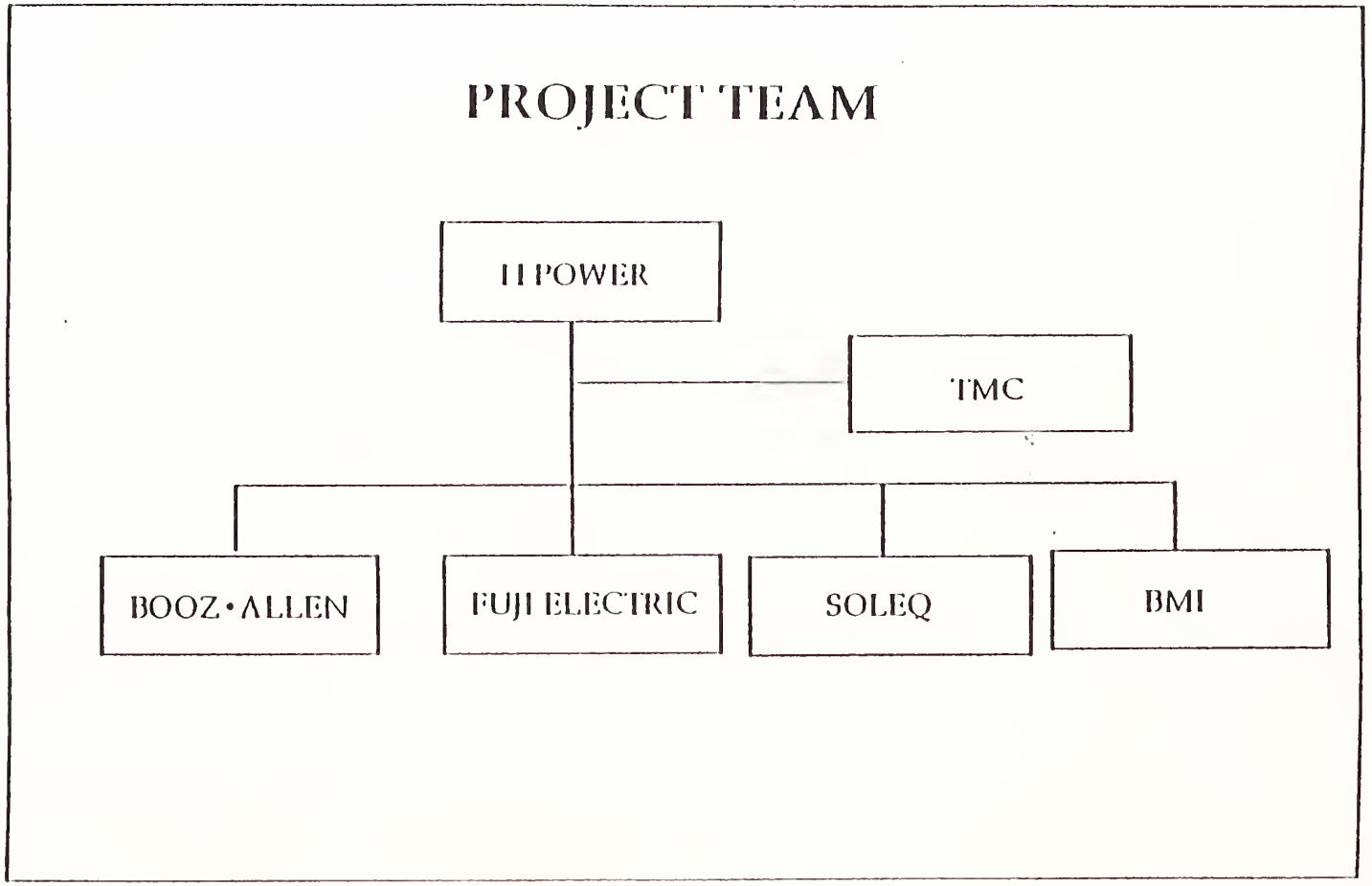
PAFC BUS
PHASE II PROJECT

- Design, Fabricate, and Test Three 29-foot Test-Bed Buses
- Utilize Demonstrated Technology
- Establish Conceptual Design for 40-ft.Transit Bus

PROJECT SCHEDULE



Feb 2, 1993


PROJECT TEAM
TI POWER
TMC
BOOZ • ALLEN
FUJI ELECTRIC
SOLEQ
BMI

BUS REQUIREMENTS

- PASSENGERS
  - SEATED 24 *
  - STANDING 13
  - PHYSICALLY IMPAIRED 2

* WITH WHEELCHAIRS UNOCCUPIED

REQUIREMENTS

• LENGTH	30 FEET MAXIMUM
• WIDTH	96 INCHES
• HEIGHT	121 INCHES
• FLOOR HEIGHT	30-34 INCHES
• RANGE	150 MILES MINIMUM
• PROVEN COMPONENTS	

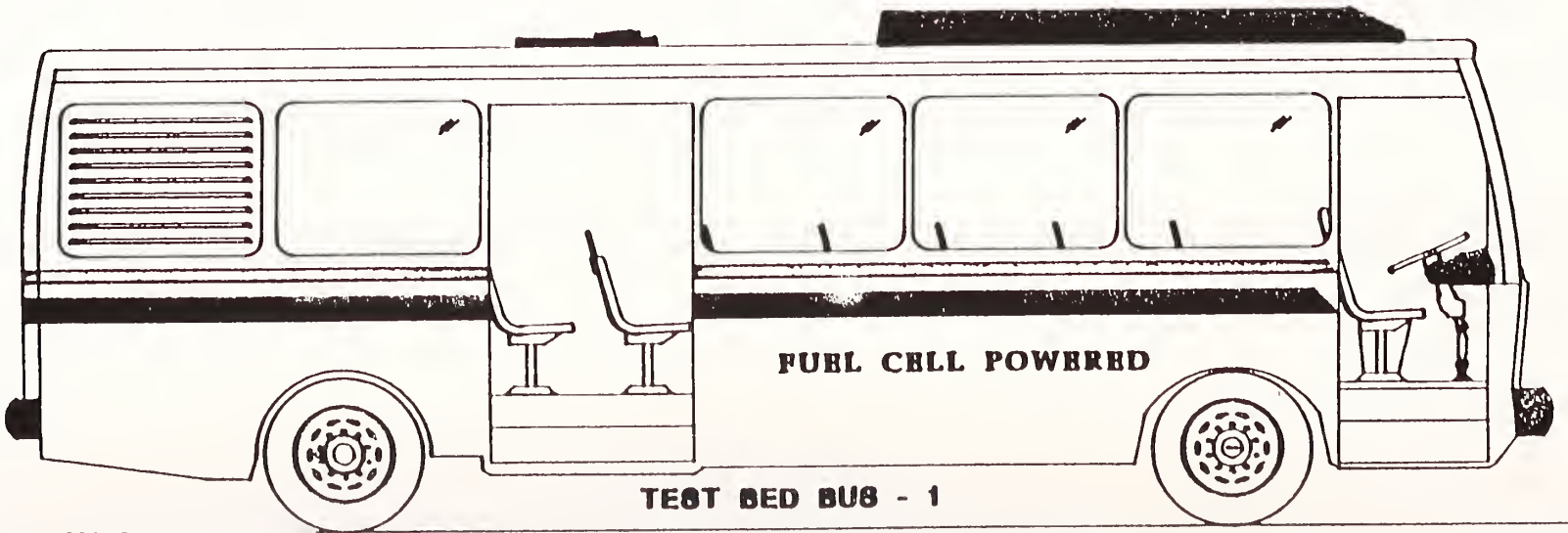
MISSION

- NON POLLUTING
- MEET THE "WHITE BOOK" REQUIREMENTS
- PERFORM ON TYPICAL TRANSIT MISSIONS
  - FTA TRANSIT COACH DUTY CYCLE
  - GEORGETOWN UNIVERSITY ROUTE (GUTS)
  - LOS ANGELES RTD LINE 16

  UNDER ALL TRAFFIC CONDITIONS

PERFORMANCE

SPEED	WHITE BOOK	PROJECTED
0-10 MPH	5.6 SEC	3.6 SEC
0-30 MPH	19 SEC	14.4 SEC
0-50 MPH	60 SEC	45.5 SEC
TOP SPEED	55 MPH	58 MPH
2.5% GRADE	44 MPH	44 MPH
12% GRADE	7 MPH	15 MPH
RANGE	150 MILES	150+ MILES

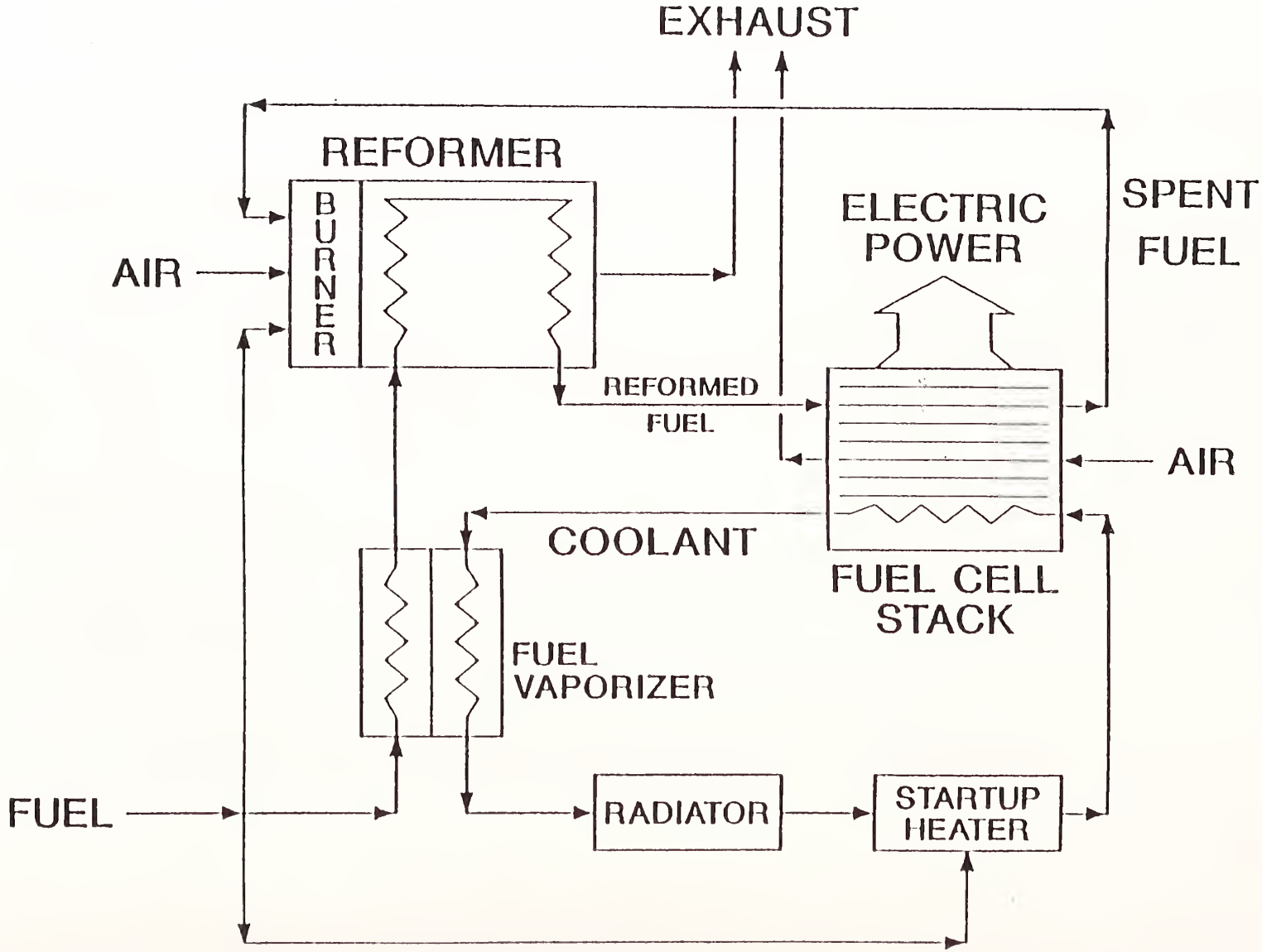


TEST BED BUS - 1

FUEL CELL SUBSYSTEM REQUIREMENTS

- PROVIDE ALL ENERGY FOR TRACTION AND AUXILIARIES
- UTILIZE COMMERCIAL-GRADE METHANOL/WATER FUEL AND AMBIENT AIR WITH ULTRA-LOW EMISSIONS
- PROVIDE POWER IN EXCESS OF AVERAGE POWER DEMAND
- PROVIDE OUTPUT FROM 0% TO 100% OF RATED POWER
- PROVIDE CONTROL FUNCTIONS INTERNALLY TO ACCOMMODATE START-UP, SHUTDOWN, LOAD CHANGES, EMERGENCIES
- PROVIDE BY-PRODUCT HEAT FOR CABIN HEATING
- PROVIDE CONDITIONED D.C. POWER TO MATCH BATTERY VOLTAGE

PHOSPHORIC ACID FUEL CELL SYSTEM



FUEL CELL SUBSYSTEM SPECIFICATIONS

RATED OUTPUT POWER

- Gross: 55.2 kW (115VDC x 480A)
- Net (DC-DC Converter Output): 47.5 kW

FUEL CONSUMPTION (premix at 1:1.5 methanol/water molar ratio)

- Methanol: 48.2 lb/hr
- Water: 40.7 lb/hr

EFFICIENCY:

- Overall System: 39% (LHV)
- Based on:
  - auxiliary component losses of 5.2 kW (gross)
  - plus DC-DC converter losses (at 95% efficiency)

FUEL CELL SUBSYSTEM SPECIFICATIONS (cont'd)

SIZE: 51.2 in. deep x 82.7 in. wide x 64.8 in. high (overall)

WEIGHT: 3921 lb

START-UP TIME:

- Cold: 30 min.
- Stand-by: 5 min.

SHUTDOWN TIME:

- Normal: 20 min.
- Emergency Immediate

RESPONSE TIME:

- 0% to 100% of Rated Power: 5 min.
- 100% to 0% of Rated Power: 5 min.

FUEL CELL SUBSYSTEM SPECIFICATIONS (cont'd)

EMISSIONS:

- NOx: < 0.18 gram/bHp-hr. (Diesel: 5.0)
- CO : < 0.55 gram/bHp-hr. (Diesel: 15.5)

NOISE: < 70 dB

VIBRATION TOLERANCE: 2.2 g (50Hz)

SHOCK TOLERANCE: 3 g (minor effects at 6 g)

AMBIENT TEMP. LIMITS: -5 to 40 deg. C (operation & storage)

FUEL CELL STACK SPECIFICATIONS

RATED POWER OUTPUT:	55.2 kW
RATED CURRENT:	480 A (240 mA/cm^2)
VOLTAGE AT RATED CURRENT:	115 V (0.66 V/cell)
NUMBER OF CELLS:	175
OPERATING TEMPERATURE:	190 deg. C (liquid-cooled)
OPERATING PRESSURE:	10 in. H_2O (max.)
COOLANT:	Aromatic hydrocarbon (NeoSK); 42 gal./min.
SIZE:	27.5 in. x 27.5 in. x 57.1 in. high
WEIGHT:	1284 lb.

METHANOL REFORMER SPECIFICATIONS

WATER / METHANOL RATIO: 1.5 (molar)

HYDROGEN DELIVERY RATE: 320-1720 ft^3/hr

METHANOL CONVERSION: > 99%

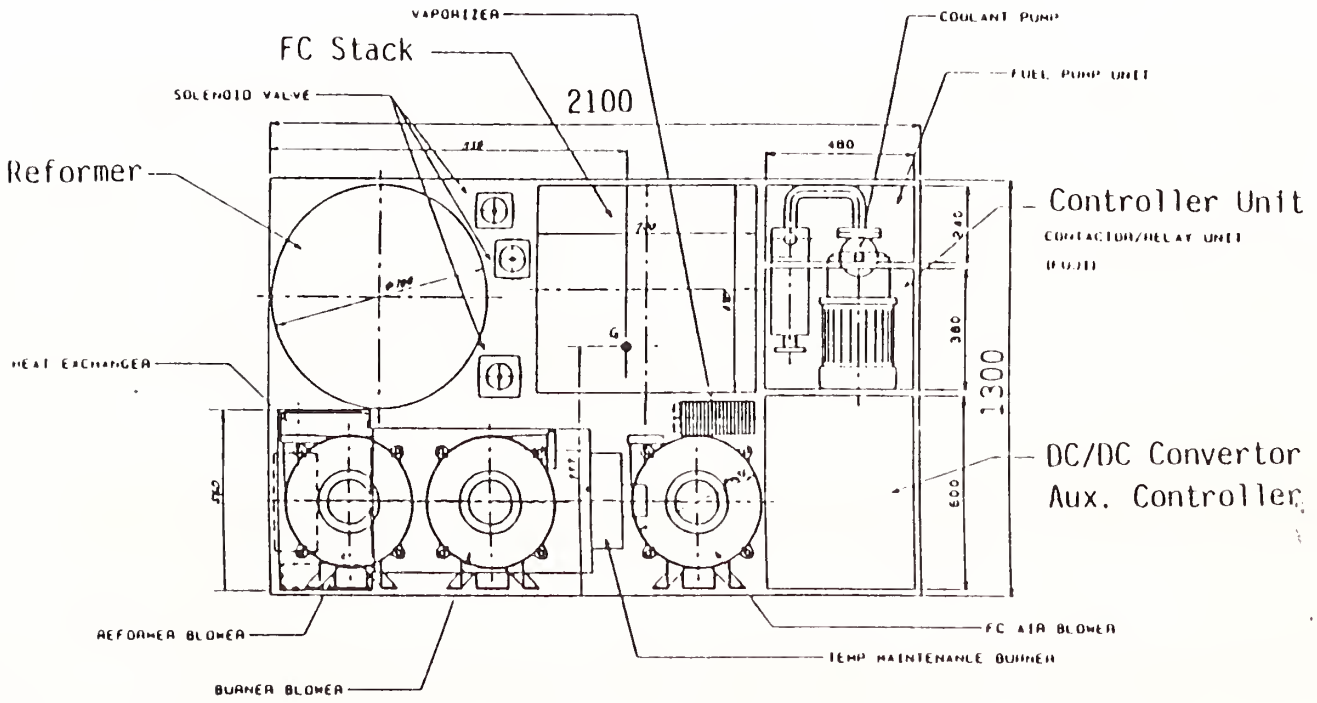
TYPICAL EFFLUENT (260 deg. C):

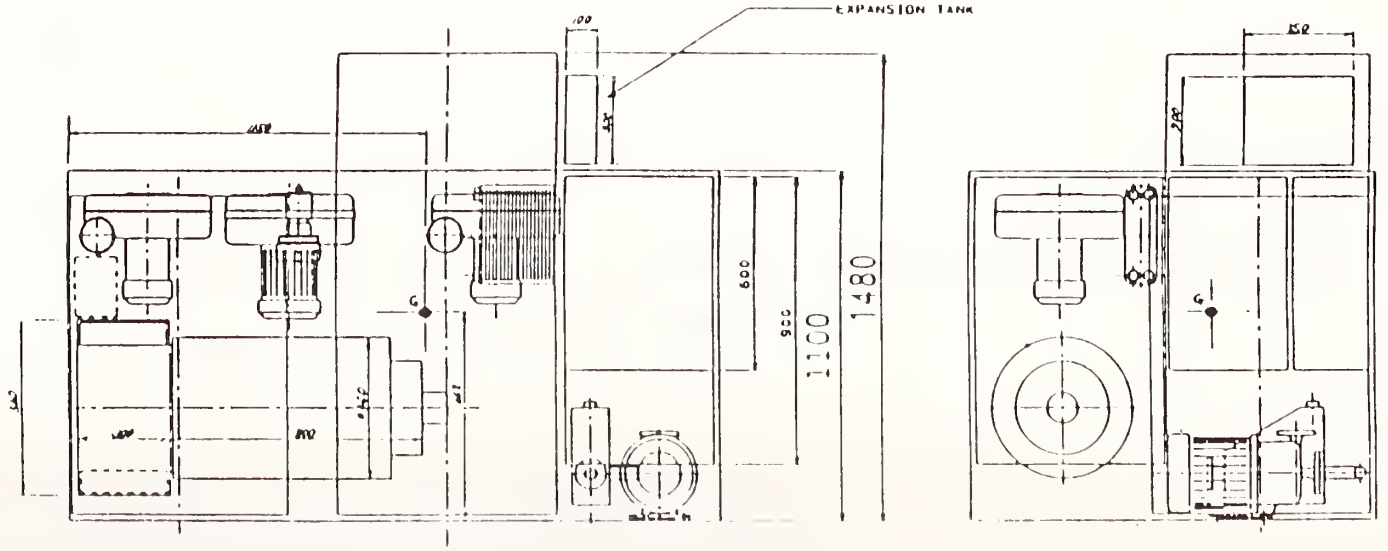
- H_2 > 65%
- CO < 2%

SIZE: 27.5 in. dia. x 43.5 in. high

WEIGHT: 485 lb.

50kW Fuel Cell Subsystem for Bus





Fuel Cell Subsystem Schedule and Status

- Detailed Design Established and Assembly/Installation Drawings Completed

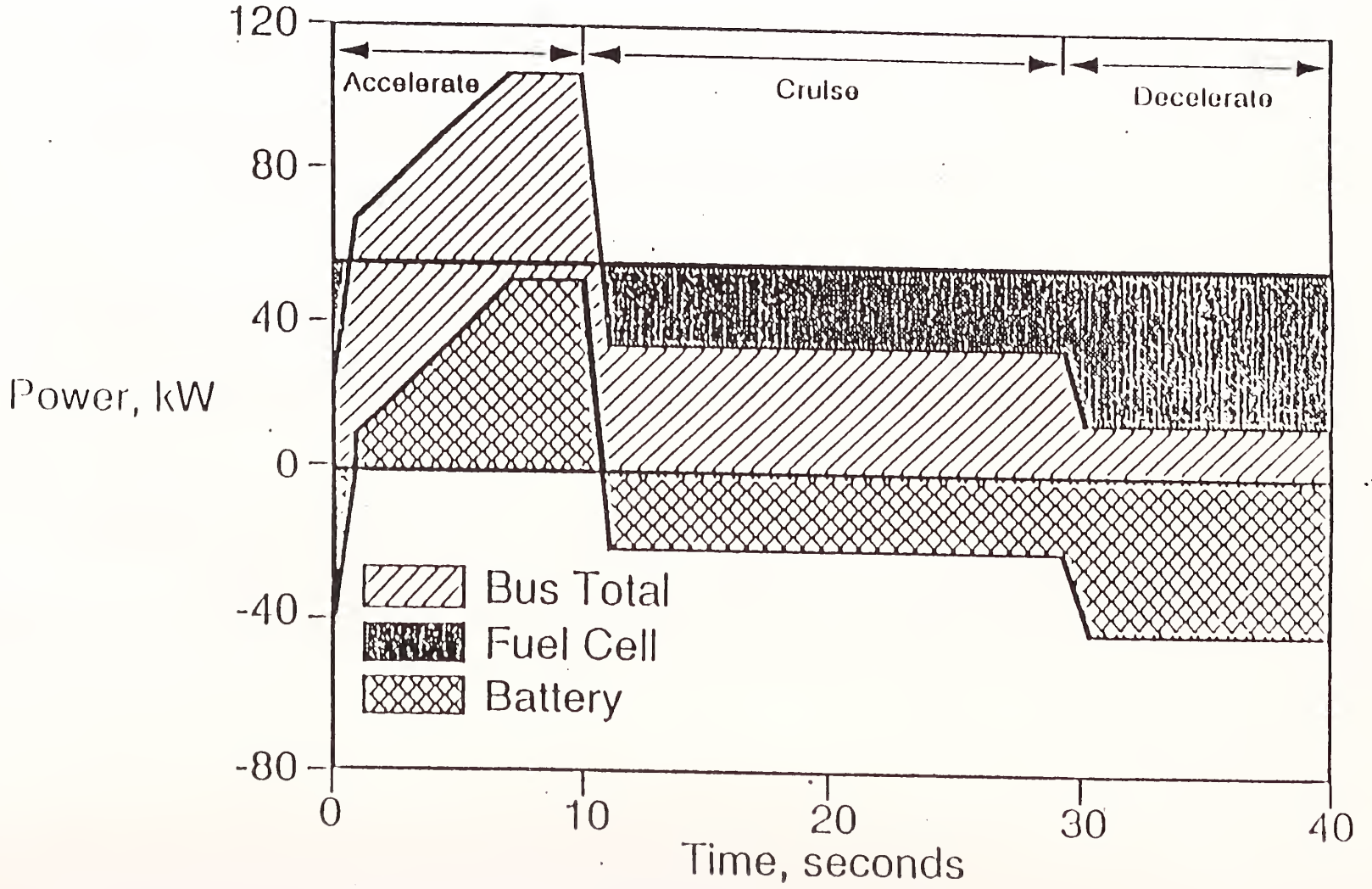
- Fabrication of Long-Leadtime Components Well Underway

- Progress Towards Delivery of 1st Fuel Cell System in August 1993 Proceeding On Schedule

- Import Issue Being Addressed
  - request for waiver of import duty being pursued
  - customs broker identified

Battery Subsystem

Power Requirements for Fuel Cell Bus



Unique Battery Requirements for Fuel Cell Bus

- Must be able to accept charge at rates nearly equal to discharge rates
  - discharge at 70 kW, charge at 60 kW
- Daily operation much more severe
  - energy throughput several times nameplate capacity
- Must be extremely rugged
  - daily operation of up to 16 hours virtually continuous

BATTERIES EVALUATED FOR FUEL CELL BUS

Battery Type	Battery Model	Manufacturer	Capacity (Ah)	Battery Wt. (lbs) (216-V System)	Life (GUTS Cycles)
Lead-Acid	4-D SLI	Exide	124	1,924	--
Lead-Acid	8-D SLI	JCI	177	2,196	940/1150
Lead-Acid	8-D	Trojan	177	--	--
Lead-Acid	MSB-2460	GNB	110	1368	--
Ni/Cd	STM-200	SAFT	200	1930	>3700
Ni/Cd	STH-1200	SAFT	115	2300	>2200
Ni/Cd	STH-800	SAFT	80	1310	--
Ni/Cd	FNC-X55	Hoppecke	2@55	1544	>2500

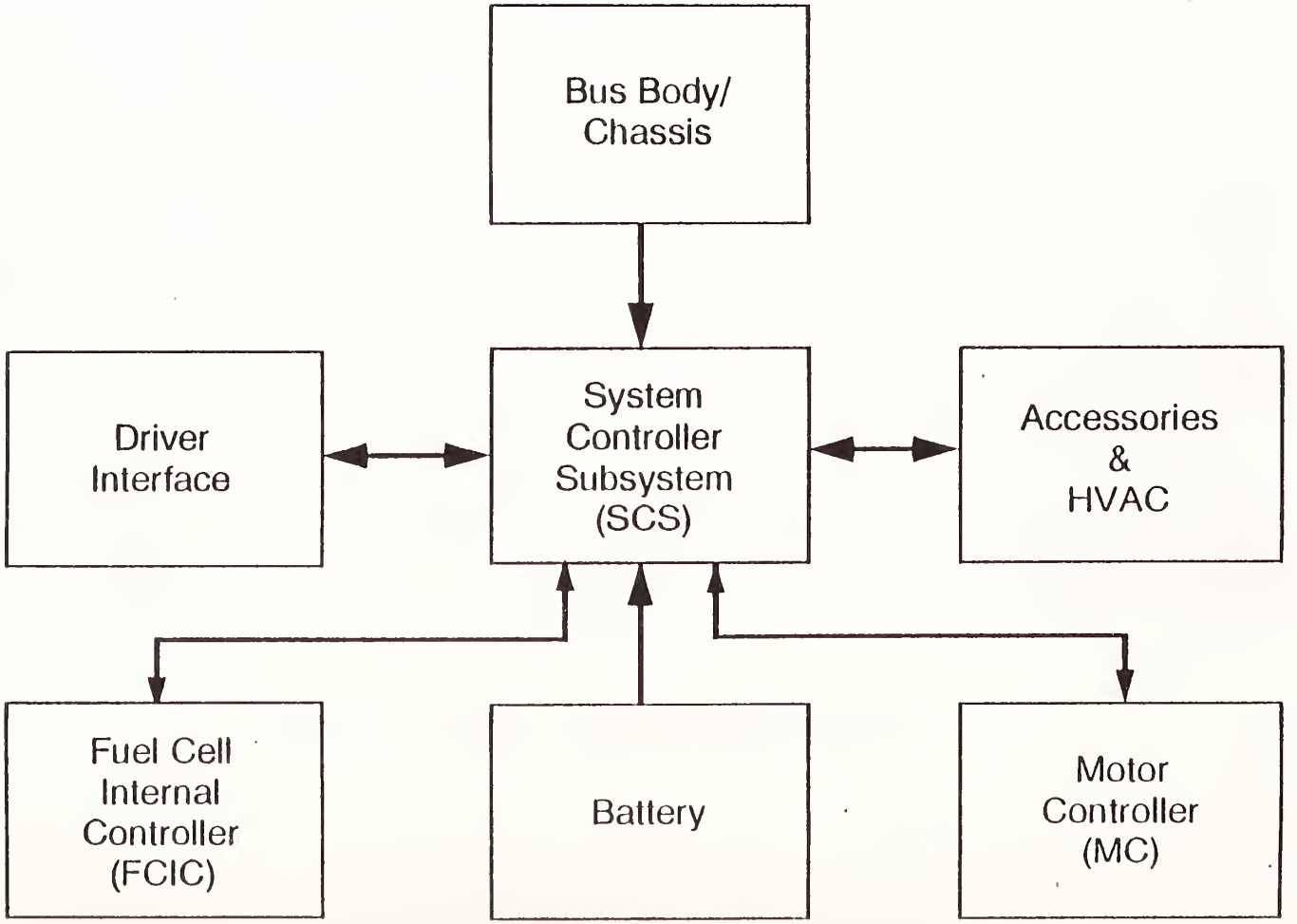
Battery Conclusions and Recommendations

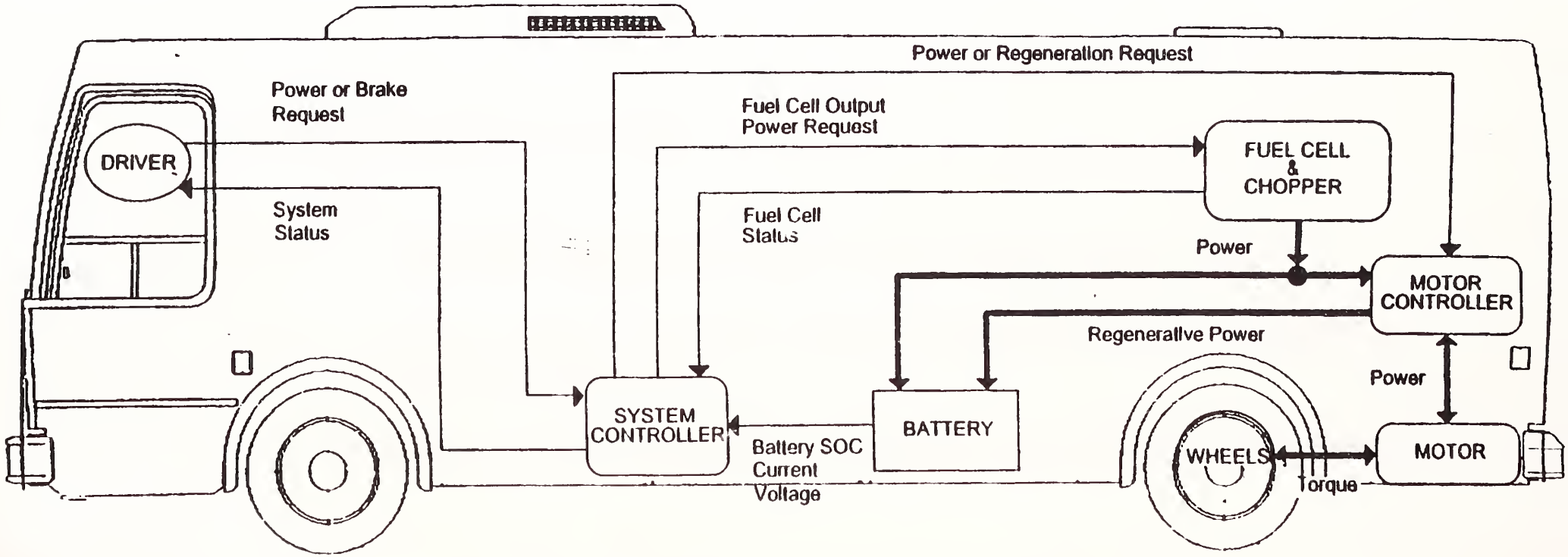
- Lead-acid batteries provide acceptable performance, but unacceptable short life for SLI designs tested to date
- Ni/Cd batteries offer good performance and lower weight, and their much longer life should offset their higher initial cost
- To ensure reliability, STM-200 Ni/Cd battery recommended for 1st Fuel Cell Bus
- Alternative batteries to be evaluated may offer potential for significant weight reduction

SCS Functions

- Energy Management
- Emergency Protocol
- Data Logging

SCS Relational Diagram



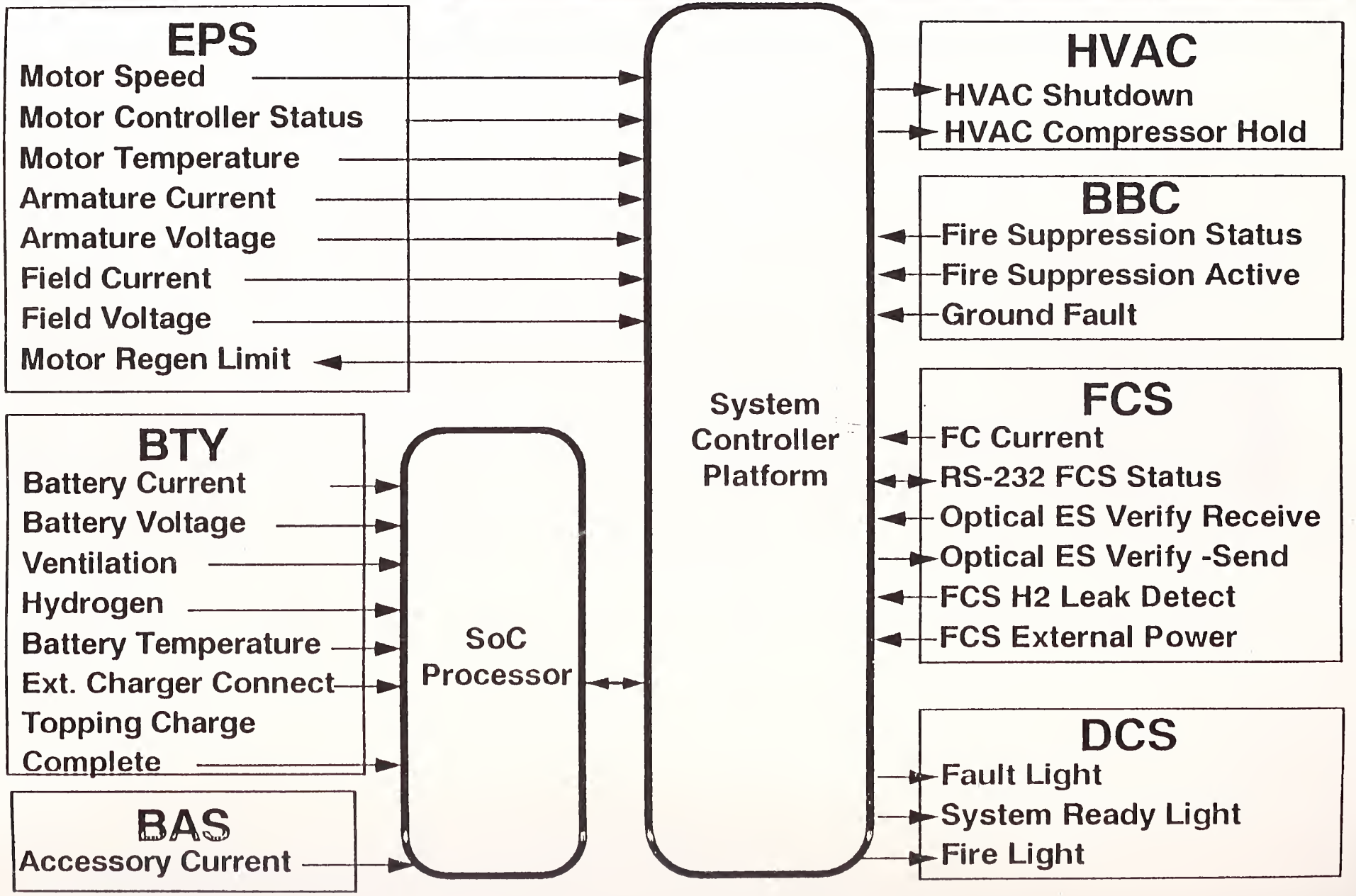


FUEL CELL BUS - HYBRID POWER SYSTEM

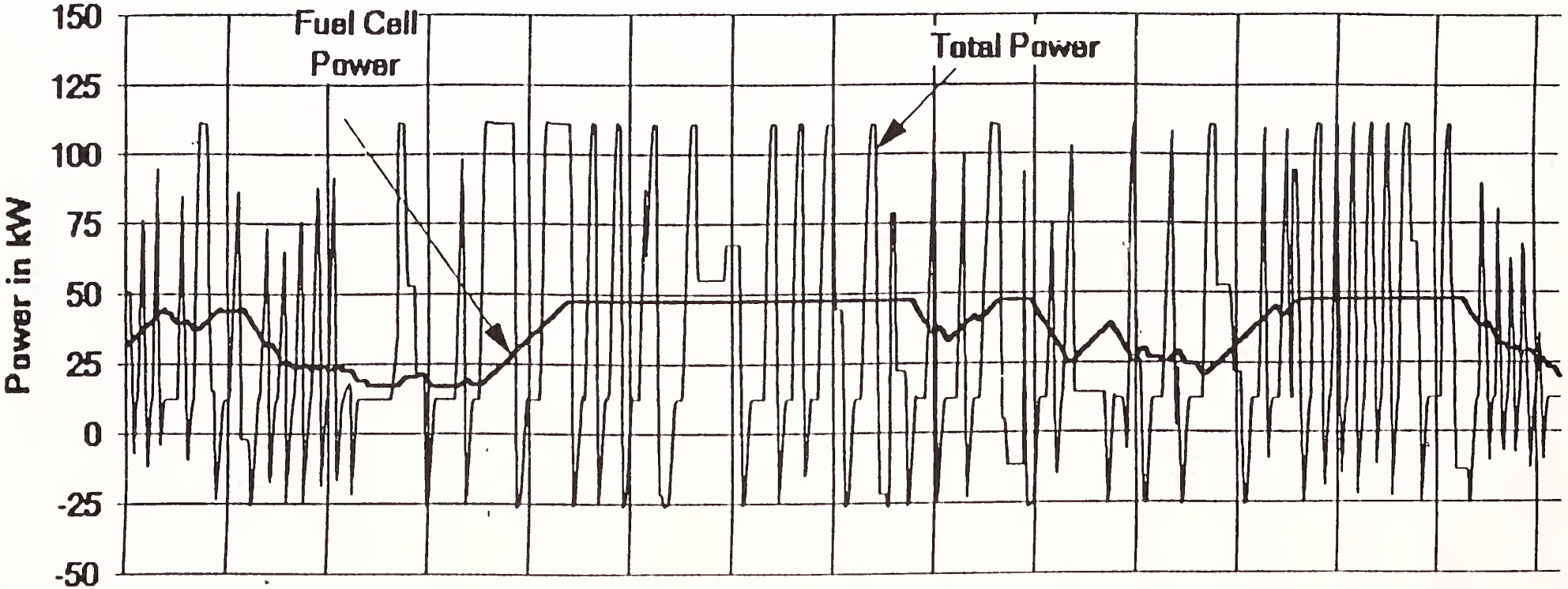
SCS Energy Management Objective

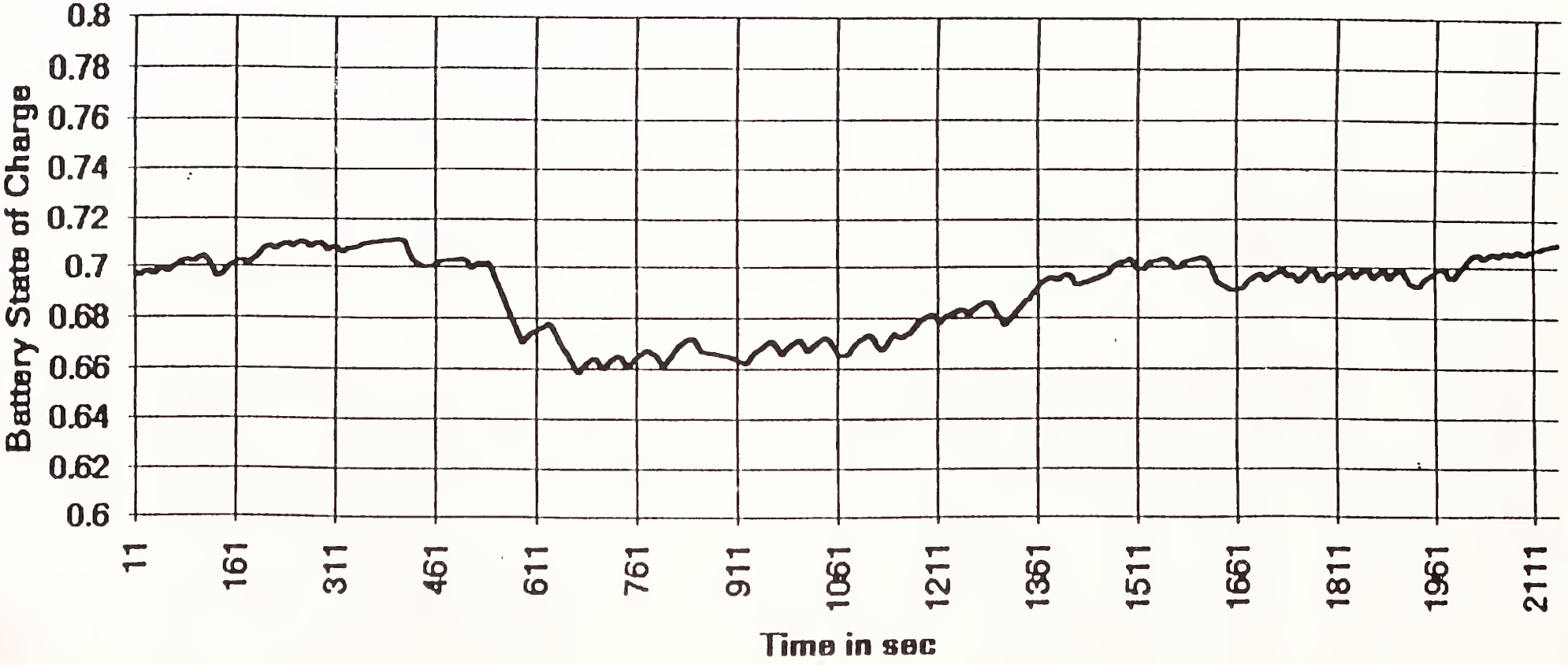
- Maximize Battery Life
  - Operations:
    - SCS Maintains Proper SoC Levels (60% - 65%)
    - SCS Uses FC Load Following Algorithm to Reduce Battery Stress
  - At Depot, SCS Monitors Battery Equalization Charges

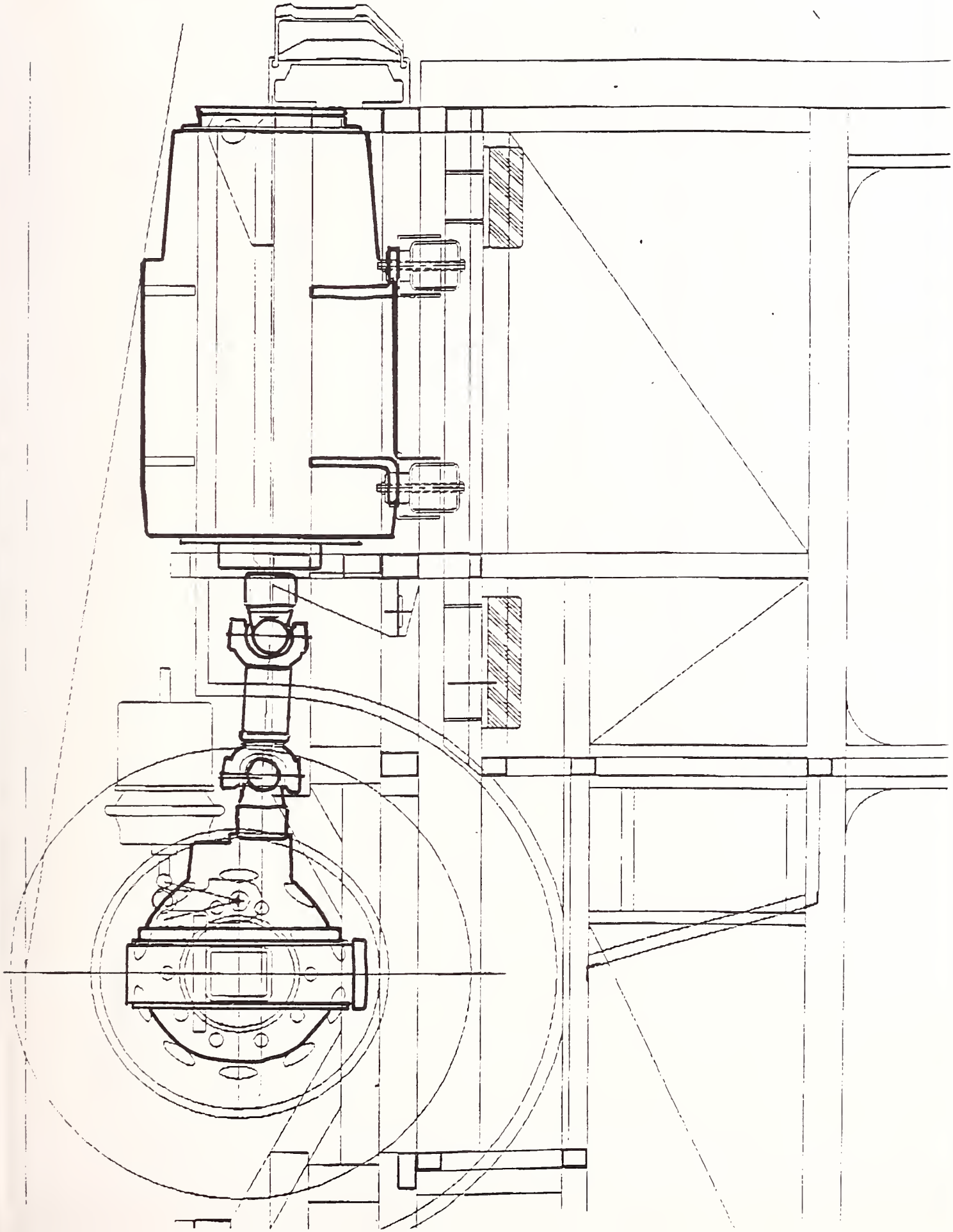
SCS Interfaces



Georgetown Route: NiCd-200 216 V 150 amp regen




Georgetown Route: NiCd-200 216 V 150 amp regen
Battery State of Charge
0.8
0.78
0.76
0.74
0.72
0.7
0.68
0.66
0.64
0.62
0.6
11
161
311
461
611
761
911
1061
1211
1361
1511
1661
1811
1961
2111
Time in sec



HVAC

HEATING SYSTEM

- Uses Waste Heat from Fuel Cell Coolant Loop
- Provides Heat for Both Driver and Passengers
- Uses Standard Heating System Components

COOLING SYSTEM

- Roof Mounted With Electrically Driven Compressor
- Lightweight System to Meet Cooling Needs of Mission
- Vendor to Customize Production System for TBB Use
- System Controller to Monitor AC & Adjust FC Output Accordingly

FUEL CELL SUBSYSTEM SAFETY

- HYDROGEN DETECTION
- FIRE SUPPRESSION
- SENSOR-ACTIVATED SHUTDOWN
- THREE-TIER SHUTDOWN HIERARCHY

FUEL CELL/BATTERY POWERED BUS SYSTEM PROGRAM:

- IS A MAJOR FORWARD STEP IN THE APPLICATION OF FUEL CELLS TO TRANSPORTATION
- WILL PROVIDE A VIABLE ALTERNATIVE TO DIESEL BUSES

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